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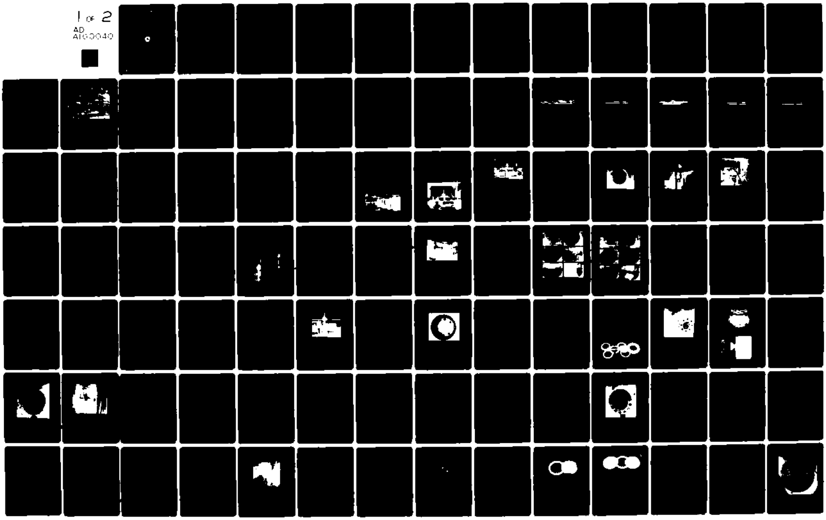

Report No. CG-D-20-81

LEVEL III

(12)

FLASHBACK FLAME ARRESTER DEVICES FOR
FUEL CARGO TANK VAPOR VENTS

R. A. BJORKLUND
R. O. KUSHIDA





FINAL REPORT
MARCH 1981

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**16. Abstract**


An experimental program was conducted to evaluate the flame quenching capability of four types of flame arresting devices suitable for installation on the fuel cargo tank vents aboard marine transport vessels. The four types of flame arresters included a single 30-mesh screen, a dual 20-mesh screen, a spiral-wound, crimped metal ribbon and a packed bed of Ballast rings. The testing in a 15.2 cm (6.0-in) diameter pipe facility simulated open environment flashback flame conditions as closely as practical. Both photographic and optical flame sensors were utilized to determine flame speed and flame penetration of the test arresters. A total of eight fuels that are representative of bulk cargos were tested. These included: (1) acetaldehyde, (2) butane, (3) ethylene, (4) diethyl ether, (5) gasoline, (6) methanol, (7) propane, and (8) toluene. All four of the test arresters successfully quenched a minimum of three flashback flames from all eight fuels with one exception, high speed ethylene flames penetrated the dual 20-mesh screen arrester on three tests. All four of the test arresters successfully withstood the sustained flame from a propane/air mixture for a test duration of 30 minutes. However, none of the arresters tested withstood the sustained flame from an ethylene/air mixture for more than 7 minutes.


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# METRIC CONVERSION FACTORS

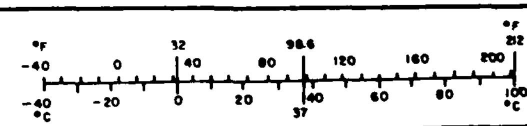
## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | **AREA** | | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | **MASS (weight)** | | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | **VOLUME** | | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | **TEMPERATURE (exact)** | | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | **LENGTH** | | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | **AREA** | | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | **MASS (weight)** | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | **VOLUME** | | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | **TEMPERATURE (exact)** | | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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SECTION I

SUMMARY

An experimental program was conducted to determine the flame quenching capability of four types of flame arresters suitable for installation on fuel cargo tank vents. The four types of flame arresters included a single 30-mesh screen arrester, a dual 20-mesh screen arrester, a spiral-wound, crimped ribbon arrester, and a packed bed of rings arrester. The tests simulated the exhaust of flammable fuel/air mixtures from a cargo tank vent into an open deck environment. Ignition of the exhaust from an external source caused a flame to flash back over a finite run-up distance to the vent stack, which was protected by a flame arrester. In some tests, the flame was sustained on the arrester for durations up to 30 minutes. The flashback flame tests used eight different fuel/air mixtures to produce flames with speeds representative of those from fuels that could be carried as bulk cargo aboard typical transport vessels. The fuels used in testing were (1) acetaldehyde, (2) butane, (3) diethyl ether, (4) ethylene, (5) gasoline, (6) methanol, (7) propane, and (8) toluene. Of these fuels, propane and ethylene were used during the facility check-out, the initial screening tests, and the sustained burning tests. The standard test condition was a fuel/air mixture at an equivalence ratio from 1.0 to 1.2 (which produced the theoretical maximum flame speed for the fuel used) and a flow velocity that was low enough, 1.52 m/s (5 ft/s), to assure flame propagation back into the inlet piping in the event of an arrester failure.

The experimental program was performed at the Jet Propulsion Laboratory's Edwards Test Station (JPL-ETS) where the existing B-Stand facility provided suitable safety protection and support activities. A photograph of this test facility is shown in Figure 1-1. The facility was modified by adding a gaseous fuel system, a large flame test chamber, and a vertically directed, sustained burning test stand. The fuel/air supply and induction system provided a continuous flow of flammable mixture into a 23.8-m (78-ft.) length of 15.2-cm- (6-in.-) diameter piping. The flame arrester test assemblies were mounted at the end of the facility piping to simulate the vent stack configuration aboard a tank vessel. Optical flame sensors, pressure sensors, and thermocouples were installed in the facility piping to witness and record any flame penetration. A 2.44-m- (8-ft.-) diameter by 4.27-m- (14-ft.-) long cylindrical chamber provided a protecting enclosure surrounding the test arrester and the flow area for a considerable distance downstream. The open ends of the test chamber were covered with a thin opaque plastic film to prevent wind dilution and dispersion of the flammable fuel/air mixture plume, but offered minimal restriction to the expanding gases after combustion. An exhaust collector and burn-off stack located at the downstream end of the test chamber maintained atmospheric pressure within the chamber before ignition, and provided a means of reducing atmospheric pollution from the unburned fuel/air mixtures passing through the chamber. Optical flame sensors, pressure sensors, and a high-speed motion picture camera were used in the flame test chamber to witness and record ignition and flame propagation. It was possible to ignite the fuel/air mixture from two different locations: (1) at the upstream end of the chamber, close to the face of the test arrester, and (2) at the downstream end of the chamber where the distance was sufficient to insure that the flame propagating upstream had achieved steady-state speed upon reaching the test arrester. The

An initial series of screening tests were made in the full-scale flame test chamber using propane/air mixtures and ethylene/air mixtures (as representative of the two extremes of probable flame speeds for typical bulk cargo fuels) to determine which igniter location (upstream or downstream) produced the most severe test conditions. The severity being identified as the highest flame speed propagating upstream towards the test flame arrester. Both the single 30-mesh screen arrester and the dual 20-mesh screen arrester were evaluated for flame quenching capability on these tests. The resulting flame speeds ranged from 2.99 to 6.60 m/s (9.81 to 21.65 ft/s) with the upstream igniter location producing the higher flame speed for both fuel/air mixtures. A tabular summary of average values of flame speeds and peak pressure rises for all fuels tested is given in Table 1-1. The single 30-mesh screen arrester quenched all flashback flames for both fuel/air mixtures. The dual 20-mesh screen arrester quenched all propane/air mixture flames and the ethylene/air mixture flames initiated by the downstream igniter location. The ethylene/air mixture flames initiated by the upstream igniter location penetrated the dual 20-mesh screen arrester in three successive test firings. A tabular summary of the flashback flame quenching test results for all fuel/air mixtures and test arrester assemblies is given in Table 1-2.

The upstream igniter location was used on all the subsequent flashback flame quenching tests. The single 30-mesh screen arrester and the dual 20-mesh screen arrester were tested with the six remaining fuel/air mixtures. Both arresters were successful in quenching the flames on all test firings as shown in Table 1-2. The resulting flame speeds, or test condition severities, for the six additional fuel/air mixtures were less than those measured for the ethylene-fuel/air mixture, as shown in Table 1-1.

The original test configuration for the packed bed of aluminum Ballast rings arrester was unsuccessful in quenching the flashback flames from gasoline/air mixtures in three successive test firings. A single 30-mesh screen was added on the downstream end of the arrester, between the retainer grid and the bed of rings. This modified configuration was successful in quenching flashback flames from the propane/air mixture, gasoline/air mixture, and three out of four test firings with ethylene/air mixture. The spiral-wound, crimped stainless-steel ribbon arrester was successful in quenching all flashback flames from propane, ethylene, and gasoline-fuel/air mixture test firings. The test results are summarized in Table 1-2.

The sustained burning tests were conducted outside of the flame test chamber by rearranging the facility piping. Using a combination of pipe elbows, the last section of inlet pipe was redirected 90 deg to one side and the flame arrester test assemblies were mounted on the end of the pipe in the vertically up position. Two different sizes of flame screen arrester assemblies were tested, (1) the original 15.2-cm- (6-in.-) diameter adapter housing and (2) a new 25.4-cm- (10-in.-) diameter adapter housing. This change in arrester flow area was made to evaluate the effects of the approach velocity and flow-through velocity of the fuel/air mixture on the thermal environment at the screens. The single 30-mesh screen arrester and the dual 20-mesh screen arrester in both pipe sizes, the packed bed of Ballast rings arrester, and the spiral-wound, crimped ribbon arrester were all successful in maintaining sustained burning with the propane/air mixture for the full 30 minutes (1800 seconds) of test duration.

Table 1-1. Tabular Summary of Flashback Flame Speed and Test Chamber Peak Pressure Rise

| Igniter Location And Type of Fuel | Average Flame Speed at Tester Arrester: Flame Sensor Data, m/s (ft/s) | Average Flame Speed at Tester Arrester: Photographic Data, m/s (ft/s) | Average Peak Pressure Rise in the Flame Test Chamber, $N/m^2$ (psid) |
|---|---|---|---|
| **Downstream** | | | |
| Propane | 2.99 (9.81) | 3.38 (11.09) | 814 (0.118) |
| Ethylene | 4.35 (14.27) | 4.02 (13.19) | 931 (0.135) |
| **Upstream** | | | |
| Propane | 4.75 (15.58) | 3.40 (11.15) | 1043 (0.151) |
| Ethylene | 6.60 (21.65) | 4.75 (15.85) | 1102 (0.160) |
| Gasoline | 4.22 (13.85) | 2.42 (7.94) | 1020 (0.148) |
| Methanol | 4.35 (14.27) | 3.18 (10.43) | 831 (0.120) |
| Toluene | 5.42 (17.78) | 3.21 (10.73) | 668 (0.097) |
| Diethyl ether | 5.61 (18.41) | 3.73 (12.24) | 937 (0.136) |
| Butane | 3.62 (11.88) | 2.90 (9.51) | 926 (0.134) |
| Acetaldehyde | 5.30 (17.39) | 4.64 (15.22) | 1102 (0.160) |

Table 1-2. Tabular Summary of Flashback Flame Quenching Test Results

| Igniter Location And Arrester Configuration | Type of Fuel and Number of Flames Quenched | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Propane | | Ethylene | | Gasoline | | Methanol | | Toluene | | Diethyl Ether | | Butane | | Acet-aldehyde | |
| | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No |
| Downstream | | | | | | | | | | | | | | | | |
| Dual 20-Mesh screens | 3 | | 3 | | | | | | | | | | | | | |
| Single 30-Mesh screen | 4 | | 3 | | | | | | | | | | | | | |
| Upstream | | | | | | | | | | | | | | | | |
| Dual 20-Mesh screens | 3 | | | 3 | 3 | | 3 | | 3 | | 3 | | 4 | | 3 | |
| Single 30-Mesh screen | 3 | | 3 | | 3 | | 3 | | 4 | | 3 | | 3 | | 3 | |
| Packed bed of Ballast rings | | | | | | 3 | | | | | | | | | | |
| Packed bed of Ballast rings with single 30-mesh screen | 3 | | 3 | 1 | 3 | | | | | | | | | | | |
| Spiral-wound, crimped ribbon | 3 | | 4 | | 4 | | | | | | | | | | | |

Sustained burning tests were also made with the ethylene/air mixture, but because of the anticipated severity of test conditions, only the packed bed of Ballast rings arrester and the spiral-wound, crimped ribbon arrester were tested. The spiral-wound, crimped ribbon arrester failed in two tests of 423 seconds and 383 seconds duration. The packed bed arrester failed on the first tests after only 43 seconds duration, and resulted in a deflagration-to-detonation transition in the arrester bed. On the second test, the packed bed arrester failed immediately after ignition due to a damaged screen. The results of the sustained burning tests are summarized in Table 1-3.

Table 1-3. Tabular Summary of Sustained Burning Test Results

| Flame Arrester Type and Size | Type of Fuel | Time Duration of Burning, s | Flamethrough |
|---|---|---|---|
| 15.2-cm- (6-in.-) diam. single 30-mesh stainless-steel screen | Propane | 1800 | No |
| 15.2-cm- (6-in.-) diam. dual 20-mesh stainless-steel screen | Propane | 1800 | No |
| 25.4-cm- (10-in.-) diam. single 30-mesh stainless-steel screen | Propane | 1800 | No |
| 2.54-cm- (10-in.-) diam. single 20-mesh stainless-steel screen | Propane | 1800 | No |
| 30.5-cm- (12-in.-) diam. by 20.3-cm- (8-in.-) long spiral-wound, crimped stainless-steel ribbon | Propane | 1800 | No |
| | Ethylene | 423 | Yes |
| | Ethylene | 383 | Yes |
| 25.4-cm- (10-in.-) diam. by 45.7-cm- (18-in.-) long packed bed of 2.54-cm- (1.0-in.-) size aluminum ballast ring plus a single 30-mesh stainless-steel screen | Propane | 1800 | No |
| | Ethylene | 43 | Yes |
| | Ethylene | 0 | Yes |

## SECTION II

## INTRODUCTION

The U. S. Coast Guard, under the Ports and Waterways Safety Act (PL 92-340), is responsible for the safety of vessels and U. S. ports from the inherent hazard of handling petroleum products. The Coast Guard must insure that cargo tanks aboard vessels are adequately protected from ignition sources that may be present on deck. Ships and barges that carry grades D and E flammable cargo are required under Subcharter D of Title 46 to have flame screens on the vent outlets of cargo tanks, cofferdams and void spaces, and on all open ullage holes, hatches, or Butterworth plates. The screens prevent accidental flame passage from the open deck into the cargo tank. A single 30-mesh screen or dual 20-mesh screens spaced more than one-half inch apart and not more than one and one-half inch apart are approved by the U. S. Coast Guard.

The adequacy of the flame screen as a flame arrester has been questioned (Reference 2-1). Wilson and Crowley (References 2-2 and 2-3) carried out tests for the U. S. Coast Guard with screen arresters, where the screens were mounted some 1.83 m (6.0 ft) inboard from the open end of the pipe, rather than at the end as in the standard vent-stack installations. These nonstandard installations were used for tests of screen arresters at high turbulent flame speeds, ranging from 2 to 30 m/s (6.6 to 98.4 ft/s). These tests of screen arresters were more severe than those where the screens were mounted in the standard installation. Under certain conditions, screen arresters failed to quench the flame in some of these tests. It seems, however, that the higher flame speeds were accompanied by gross gas motions that caused apparent discrepant flame quenching results. Because the Wilson and Crowley test conditions were not representative of flashback-flame propagation to a standard vent-stack installation in an open environment, more tests that simulated the actual conditions existing aboard fuel cargo transport vessels were needed. One of the major points of interest is whether or not a flame will accelerate in an open deck environment and what effect this accelerated flame speed has on the quenching capability of the screen arrester.

Screen flame arresters mounted at the end of a vent stack are designed to prevent flames ignited outside the tank from propagating into the tank. It is assumed that the flammable gases in the vent stack are either quiescent or flowing out. On the other hand, most of the reported tests on screen flame arresters confine the flame in an enclosure whose only or major outlet was through the flame arrester (Reference 2-4). Combustion within an enclosure is invariably accompanied by considerable gas flow through the screen in the direction of flame propagation. The hypothesis to be tested was whether an unconfined turbulent flame flashback can be stopped from propagating into a vent stack whose end is covered with a screen flame arrester. In these tests, it was supposed that there is no gross gas flow through the screen associated with the ignition and propagation of the flame.

Screen flame arresters are designed to completely enclose the outlet openings with a fine wire mesh. The wire mesh is sufficiently open so that it offers negligible obstruction to the passage of gases and vapors, but the mesh openings are too small to allow the passage of flames. There should be no opening in the screen flame arrester with an equivalent hydraulic diameter[1] larger than the critical diameter of flame quenching in a tube. The critical diameters for flame quenching in a tube for a large variety of different flammable gas mixtures have been established in extensive laboratory tests, as discussed in Wilson and Attalah's review of flame arresters for cargo venting systems (Reference 2-5). It has been shown for laminar flames propagating in flammable gases that the correlation for the critical Peclet number (Pe) (Reference 2-4) is:

$$\log_{10} Pe = 1.8 \pm 0.3$$

Pe is defined as $D_{CR} \times Su/\alpha$, where $D_{CR}$ is the critical diameter for flame quenching in a tube, Su is the laminar flame velocity in the unburned mixture, and $\alpha$ is the thermal diffusivity in the unburned mixture. The uncertainty in the value of $\log_{10}$ Pe allows for differences in the behavior of widely different fuels and oxidizers, but it is sufficiently restrictive to yield useful design values for the maximum allowable opening sizes in flame arresters.

The concept of quenching a laminar flame in a narrow tube through heat loss to the walls of the tube is well established (Reference 2-5). For effective flame quenching, the surface must be noncatalytic (this requirement is satisfied by all commercial materials of construction) and heat dissipative (stainless steels have adequate conductivity). Screen flame arresters differ from isolated orifices of the flame quench theory in that there are arrays of orifices. Each orifice in the array acts identically to an isolated orifice as far as flame quenching is concerned. Gas flows and heat transfer associated with flame propagation and gas volume expansion seem to be the main causes of screen failure. The flame heats and weakens the wires of the screen so that fluid friction and pressure tear openings into the wire mesh (References 2-6, 2-7, and 2-8). It is evident that prolonged exposure to sustained burning will decrease the quenching capability of the screen arrester, a phenomena that requires further investigation.

Flames propagating in open environment are almost invariably turbulent, as opposed to the laminar flames considered in the quenching theory (Reference 2-9). For most practical considerations, open turbulent flames can be considered highly wrinkled laminar flames whose characteristic wrinkle dimension is in the order of the critical diameter for flame quenching. The heat release rate is proportional to the total area of the propagating wrinkled flame front, which can be many times larger than the superficial projected flow area. The criterion for the critical diameter for flame quenching by the flame arrester is the same for turbulent and laminar flames according to Reference 2-4, but the heating effects of the turbulent flame are very much greater. In addition, the nonuniform and fluctuating turbulent flame front can cause, in pockets of the flame, the release of transient high pressure and high heat that far exceed in value the pressure and heat of a laminar flame (Reference 2-11). If a transient high reactivity pocket of gas coincides with the intersection of the flame front and the screen flame arrester, there is a probability that the flame will penetrate the screen

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[1] Equivalent hydraulic diameter $= \dfrac{4 \times \text{(cross-sectional area of passageway)}}{\text{perimeter of passageway}}$

at that location. To prevent such flame penetration, conservative design practice would call for screen openings substantially smaller than the theoretical critical diameter for flame quenching. These considerations are probably the reason that Rozlovskii and Zakaznov's review (Reference 2-4) presents such a wide range of critical Peclet numbers reported by different investigators in simulations of practical fire environments.

It is important to make a distinction between "burning velocity" and "flame speed" (Reference 2-9). Burning velocity is defined as the speed of the propagation of a flame front relative to the speed of the unburned gas. It is a property of the gas composition and of the physical state of the unburned gas mixture. Flame speed is defined as burning velocity plus any gross motion in the unburned gas relative to a fixed frame of reference. It is influenced by gross gas motion and by the geometry of any enclosing structure.

The propagation of a flame in a duct can create gross gas motion. This is clearly illustrated if we consider a duct, closed at one end and open to the atmosphere at the other, filled with a flammable gas. When the gas is ignited at the closed end of the duct, the flame speed is greater than it would be if the flame were started at the open end and allowed to travel toward the closed end. In the case of closed end ignition, the burned gas is expanding and pushing the unburned gas out the open end of the duct, so that the "flame speed" is the sum of the "burning velocity" and the gross motion, which is caused by the expansion of the trapped hot combustion products. In the second case, the ignition at the open end causes the unburned gas to remain stationary, hence the observed "flame speed" is nearly the "burning velocity" with differences due mainly to flame front interaction with the duct wall.

While gross gas motion does not change burning velocity by itself, there are additional factors that cause enclosed turbulent flames to accelerate in burning velocity. Acceleration of turbulent flames in ducts has been discussed in a previous JPL report (Reference 2-10) in connection with transition from deflagration to detonation. Little understood interactions between turbulent flame propagation and the turbulent boundary layer on a duct wall can lead to appreciable acceleration of the burning velocity. The flame can be accelerated to such a high speed that shock waves become associated with the highly turbulent flame front, whereupon compressive heating causes still greater acceleration until detonation is obtained. In a confined duct, particularly in those with rough walls, turbulent flames can readily accelerate to the point where self-compressive ignition occurs. The transition from deflagration to detonation in hydrocarbon-fuel/air mixtures is an extremely improbable event in an open environment, but detonations can be initiated by a shock wave from an external source, such as a bomb (Reference 2-11).

Pipes carrying vapors out of cargo tanks that contain volatile flammable liquids may contain a fuel/air mixture within the flammable range, as illustrated in Figure 2-1. A source of flame ignition outside the vent stack, as illustrated in Figure 2-2, may cause a flame to propagate into the vent stack. Flame propagation within a narrow pipe is particularly dangerous, because both confinement of the expanding hot combustion products and flame front acceleration due to interaction with the wall boundary layer can occur. In severe cases, the flame propagation can become a destructive detonation wave. The illustration in Figure 2-2 shows a flame front accelerating inside a pipe in contrast to the uniform rate of propagation in the open air.

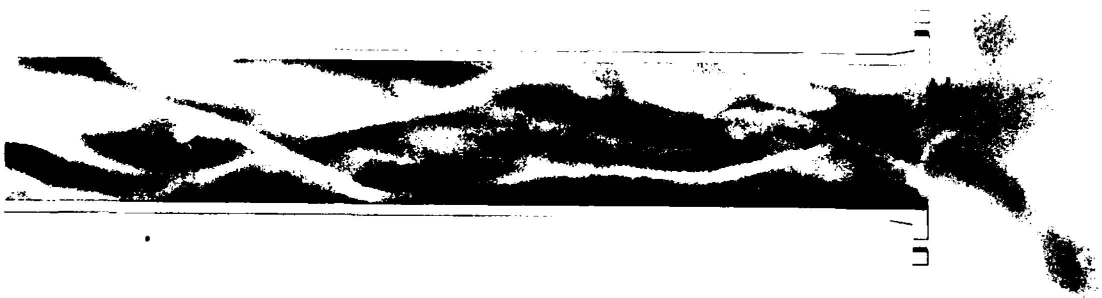


Figure 2-1. A Flammable Fuel/Air Mixture Flowing Slowly Out of a Vent Stack Into the Open Air

The installation of a simple screen flame arrester to close the open end of the vent stack to flames while still allowing free flow of vent vapors is shown in Figure 2-[illegible]. Here the flame from an outside ignition source does not propagate into the vent stack, but impinges on the surface of the screen. If the equivalent hydraulic diameter of the openings in the wire mesh of the screen flame arrester are smaller than the critical diameter for flame quenching, then the flame will be stopped by the screen. The concept and theory of the critical flame quench diameter has been reviewed by Wilson and Attalah (Reference 2-5). The flame, can, however, continue to burn on the surface of the screen if there is a flow of flammable mixture through it. The continued heating can lead to flame flashback if the wire screen's temperature becomes high enough. One element of the program was to test susceptability to flashback due to continued burning on the surface of the screen flame arrester.

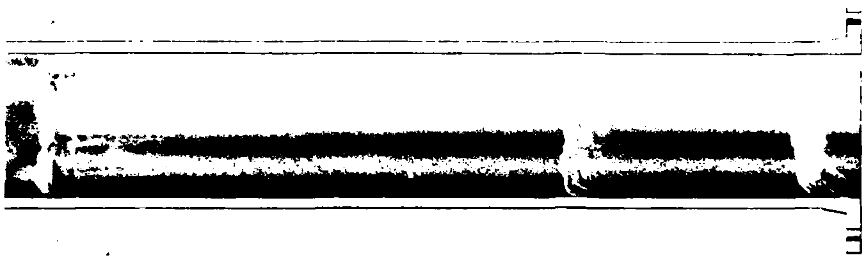


Figure [illegible]. An External Ignition Source Sends a Spherically Expanding Flame Front Propagating Into the Flammable Mixture in the Vent Stack

If the screen is mounted internally in the vent stack as shown in Figure [illegible], the flame arresting effectiveness of the screen is reduced. Upon entry into the open end of the vent stack, the flame accelerates. The accelerated flame speed causes the pressure to rise ahead of the flame front, and, if severe enough, push the flame through the screen. The gas flow in the pipe can be momentarily reversed so that the flame front and the gas flow both propagate in the same direction, which is through the screen flame arrester. Once the flame has penetrated the screen, the situation is even more dangerous since the failed screen flame arrester now acts as a barrier to hot gas flow, and thus causes an even greater acceleration of flame speed and a greater likelihood of detonative combustion.

Figure 2-[illegible]. A Propagating Flame Front Impinges on a Screen Flame Arrester Mounted on the End of the Vent Stack and [illegible] the Piping

[illegible] flame arrester damaged by a hole may fail to arrest a propagating flame [illegible] diameter is larger than the critical diameter for flame propagation. The subsequent propagation of the flame in a duct, illustrated in Figure 2-[illegible], is [illegible] than if the duct were unprotected by a screen, [illegible] damaged screen flame arrester acts as a flow obstruction to the [illegible] and causes a higher flame speed. The effect of constricting the outlet [illegible] is illustrated by Wilson and Crowley's (References 2- and 2-[illegible]) use of a [illegible] to promote high flame speeds in their flame [illegible]. [illegible] flow obstruction on a duct outlet was used to obtain deflagration [illegible] flame arrester tests of the Jet [illegible] Reference 2-[illegible].

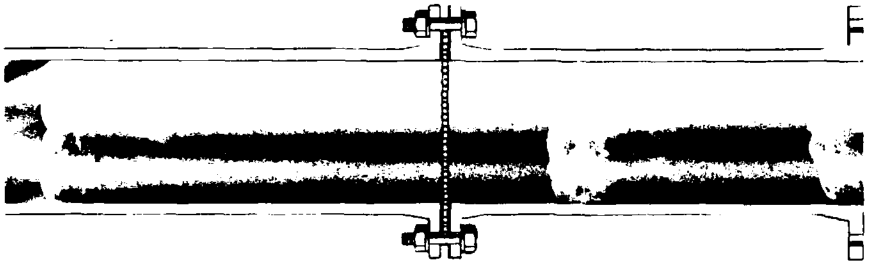


Figure [illegible]. An Internally Insulated Steel Flame Arrester [illegible] by an Accelerating Flame in the Test Stack Piping

The physical properties useful in analysis of the experimental work reported herein are listed for convenient reference. In Table [illegible], the [illegible] name, the chemical name (International Union of Chemistry nomenclature), chemical formula, and molecular weight are listed. Some of these fuels possess other common or trade names in commerce, but the listed names should be adequate to identify the material completely.

In Table [illegible], basic flame properties are listed (Reference [illegible]). The stoichiometric fuel-air ratio [illegible] is the minimum mass of air necessary to burn the fuel to carbon dioxide and water. The maximum burning velocity is the maximum value reported for the fuel burning in air at [illegible]°C and one atmosphere of pressure. [illegible] [illegible] ratio of the fuel-air ratio at which the maximum burning velocity is observed to the stoichiometric [illegible]. [illegible]

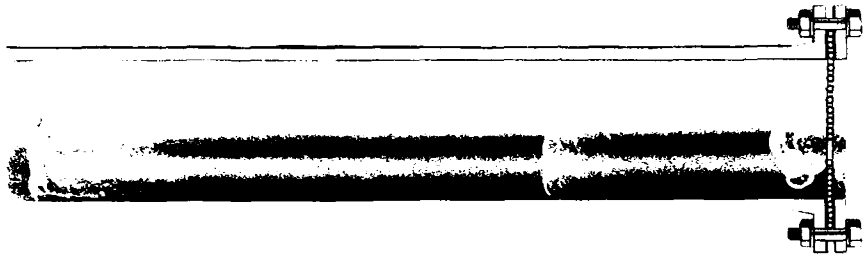


Figure [illegible]. A Propagating Flame Penetrates a Damaged Screen Flame Arrester and Accelerates in the Piping

[illegible] the first is at the stoichiometric air fuel ratio, and the second is at [illegible] of the quenching diameter—equivalence ratio curve. For all practical purposes, the equivalence ratio for minimum quenching diameter coincides with the equivalence ratio for maximum burning velocity. The spontaneous ignition temperature as determined in an ASTM test is given. The equivalence ratio for the lean [illegible] limit for upward propagation in a closed tube is listed. These values [illegible] from the flammability limit for downward propagation, hence are more [illegible] of the prevailing conditions for ignition in the flame arrester tests. [illegible] temperature conditions where fuel-vapor/air mixtures [illegible], and one atmosphere pressure.

Table 2-1. Properties of Selected Fuels

| Common Name | Chemical Name | Formula | Molecular Weight |
|---|---|---|---|
| Acetaldehyde | Ethanal | $CH_3CHO$ | 44.053 |
| Butane | n-Butane | $C_4H_{10}$ | 58.123 |
| Diethyl ether | Ethoxy ethane | $(C_2H_5)_2O$ | 74.122 |
| Ethylene | Ethene | $C_2H_4$ | 28.054 |
| Gasoline | — | $C_8H_{15.44}$ | 111.44 |
| Methyl alcohol | Methanol | $CH_3OH$ | 32.042 |
| Propane | Propane | $C_3H_8$ | 44.096 |
| Toluene | Methyl benzene | $C_6H_5CH_3$ | 92.140 |

Table 2-2. Combustion Properties of Selected Test Fuels

| Fuel | Stoichiometric[a] ($\phi = 1.0$) Air/Fuel Mass Ratio | Laminar[b] Burning Velocity, cm/s | Equivalence Ratio = ($\phi$) at Maximum Burning Velocity | Quenching Diameter of Tube, cm | | Spontaneous Ignition Temperature, °C (°F) | Lean Flammability Limit for Upward Propagation in a Closed Tube $\phi$ |
|---|---|---|---|---|---|---|---|
| | | | | Stoichiometric | Minimum | | |
| Acetaldehyde | 7.85 | (50)[c] | (1.15)[c] | 0.35 | ----[d] | 175 (347) | 0.50 |
| Butane | 15.46 | 45 | 1.13 | 0.46 | 0.28 | 430 (807) | 0.54 |
| Diethyl ether | 11.19 | 47 | 1.15 | 0.38 | 0.31 | 186 (366) | 0.55 |
| Ethylene | 14.79 | 81 | 1.15 | 0.20 | ---- | 490 (914) | 0.41 |
| Gasoline | 14.62 | 40 to 42 | 1.10 | ---- | ---- | 371 (700) | 0.60 |
| Methyl alcohol | 6.47 | 56 | 1.01 | 0.28 | 0.23 | 470 (878) | 0.48 |
| Propane | 15.68 | 46 | 1.14 | 0.31 | 0.28 | 504 (940) | 0.51 |
| Toluene | 13.50 | 41 | 1.05 | ---- | ---- | 468 (1054) | 0.43 |

[a]Composition of air: $N_2$, 78.087; $O_2$, 20.946; $CO_2$, 0.033; Ar, 0.934, in volume percent.

[b]At one atmosphere, 25°C mixture.

[c]Estimates.

[d]Data not available.

## SECTION III

## TEST FACILITY DESCRIPTION

### A. GENERAL

All testing for this program was performed at the B-Stand facility of the Jet Propulsion Laboratory's Edwards Test Station. The B-Stand test area contains an air compressor system, fuel system, fuel vaporizer and condenser loop, fuel and air induction system, facility piping, test flame chamber, and an exhaust-burn stack. The test facility flow system schematic diagrams are shown in Figures 3-1 and 3-2. Table 3-1 gives a description of the symbols used in the schematic diagrams. A detailed description of the major portion of this test facility is given in Reference 2-10. Some modifications and additions were made to incorporate gaseous-type fuels, flashback flame testing, and sustained burning testing for this program.

The following is a brief description of the various facility systems including the modifications and new additions.

### B. AIR COMPRESSOR SYSTEM

A new multistage centrifugal turbine air compressor was installed, which is rated for 11.3 $m^3$/min (400 indicated cfm) at 41.4 kN/$m^2$ (6.0 psid). It is driven by a 14.9-kW (20-hp) electrical motor. Air flow in the 10.2-cm- (4-in.-) diameter pipe system is controlled by a remotely operated metering valve and a remotely operated bypass valve. Flow rate is measured using a Meriam Laminar Flow Element (LFE).

### C. FUEL SYSTEM

Two parallel systems provide a variety of either liquid or gaseous fuels. Liquid fuel was supplied by a nitrogen gas pressurized tank with a capacity of 0.049 $m^3$ (13 gal) and a working pressure of 6895 kN/$m^2$ (1000 psia). Fuel flow was controlled by a remotely operated metering valve and measured with a turbine-type flowmeter. Gaseous fuel was supplied from a manifold containing two type-1A shipping cylinders having the combined volume of 0.0876 $m^3$ (3.08 $ft^3$). The normal delivery pressure was 8274 kN/$m^2$ (1200 psia). Gas flow was controlled by a remotely operated pressure regulator and measured with a precision-bored sonic orifice. The fuel gas temperature was stabilized for flow measurement using a water bath preheater.

### D. FUEL VAPORIZER AND CONDENSER LOOP

All fuels were either vaporized or preheated with a remotely regulated electrical heat exchanger before injection into the flowing air stream. A pneumatically operated three-way valve energized to the RUN position directed the heated fuel into the fuel injection manifold. With the valve in the CONDENSER position, the heated fuel was directed into a water bath heat exchanger where most of the

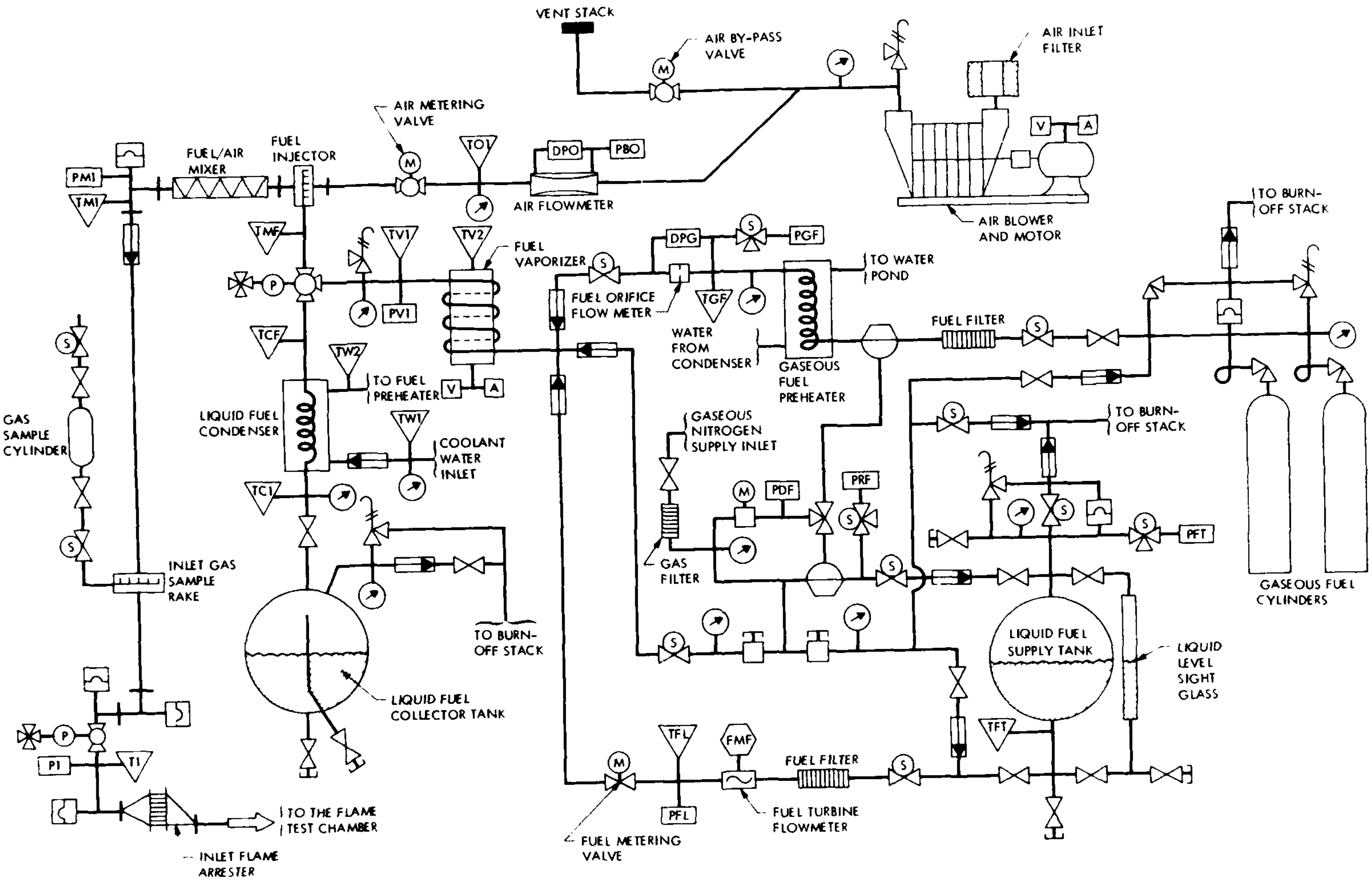



Figure 3-1. Test Facility Fuel and Air Systems Schematic Diagram with Instrumentation Locations for Flame Arrester Testing

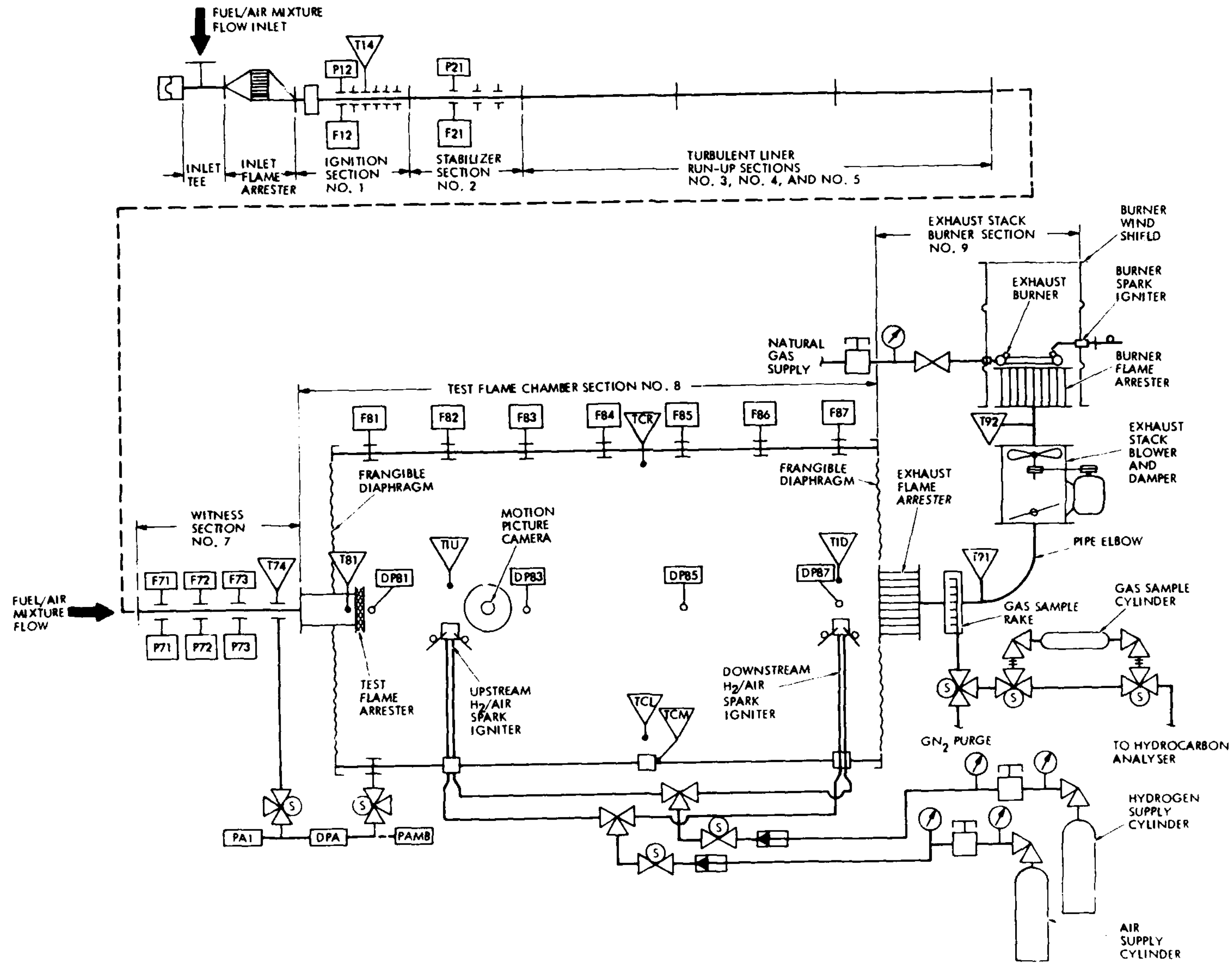
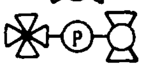



Figure 3-2. Flashback Flame Test Chamber Flow System Schematic Diagram with Instrumentation Locations for Flame Arrester Testing

Table 3-1. Symbols and Descriptions for Flow System Schematic Diagram

| Symbol | Description |
|---|---|
|  | Manual globe valve |
|   | Electric solenoid operated valve |
|   | Electric motor operated valve |
|   | Electric motor operated ball valve |
|   | Air piston operated ball valve |
|  | One-way flow check valve |
|  | Pressure relief safety valve |
|  | Dome pressure regulator valve |
|  | Manual set pressure regulator valve |
|   | Electric motor operated pressure regulator valve (dome loader) |
|  | Pressure rupture disc assembly |
|  | Pressure gage |
|   | Voltmeter transducer |
|   | Ammeter transducer |
|   | Temperature transducer |
|   | Pressure transducer |
|   | Flame sensor transducer |
|   | Flowmeter transducer |

Fog [illegible]. [illegible] were [illegible].

## E. [illegible]

Fuel was injected [illegible] the air stream [illegible] in the [illegible]-cm- ([illegible]-in.-) diameter piping. [illegible] mixer [illegible] turbulent mixing of the fuel/air mixture. [illegible] one-way flow check valve in the piping provided protection against back pressure spikes caused by flame flashbacks in the facility piping. [illegible] graph of the [illegible] air, fuel, fog [illegible], [illegible], and [illegible] system is given in Figure [illegible].

## F. [illegible]

The fuel/air mixture was [illegible] of extra-strong [illegible]-cm- ([illegible]-in.-) diameter piping. A detailed description of various sections of this piping is given in Reference [illegible]. Briefly, the facility piping contains instrumentation ports for mounting temperature, pressure, and optical flame-sensing transducers. The inlet end of this piping is [illegible] mounted into a thrust button [illegible] withstand any pipe [illegible] detonations. There [illegible] high-pressure pipe transition section in the inlet that houses a spiral-wound, crimped stainless-steel ribbon arrester. This arrester quenched any propagating flames or detonations that penetrate into the facility piping from the test section. The hydrogen/air spark igniter was removed from the inlet ignition [illegible]

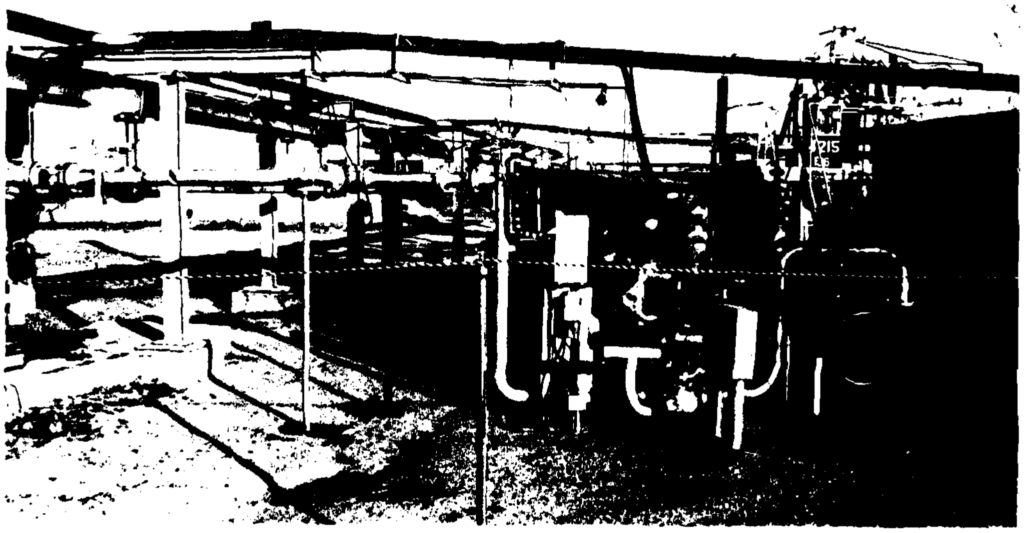
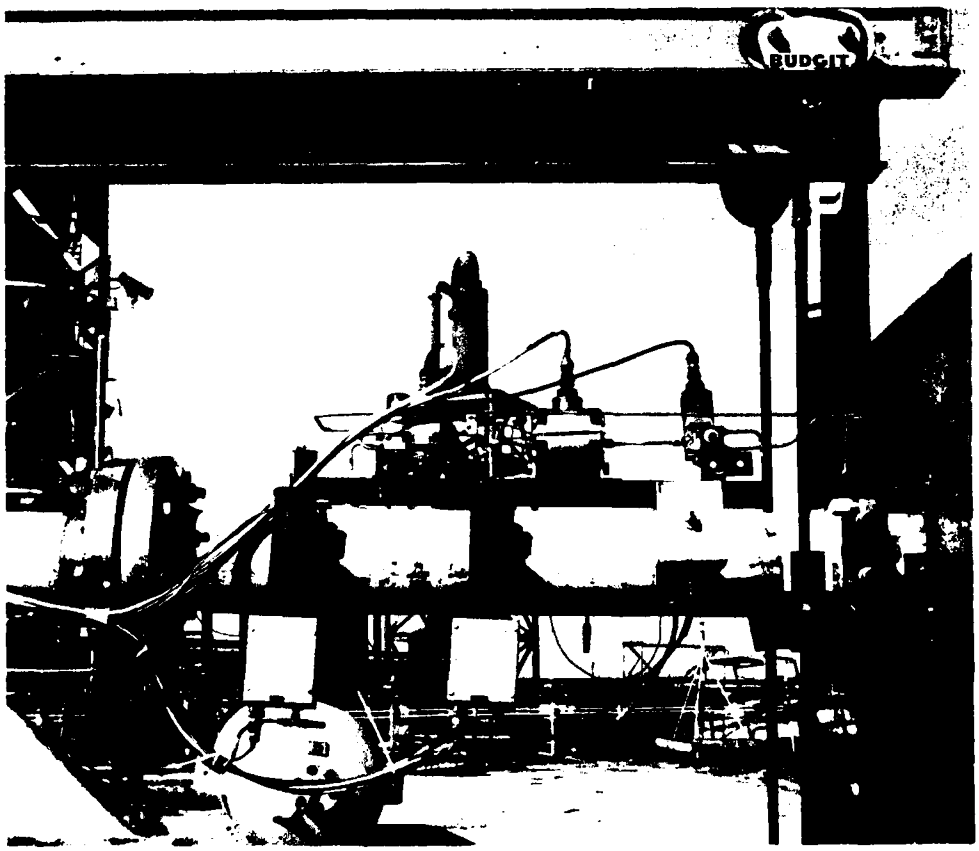



Figure [illegible]. [illegible] Air, Fuel, Fog [illegible], [illegible], and [illegible] System [illegible]


BUDGIT

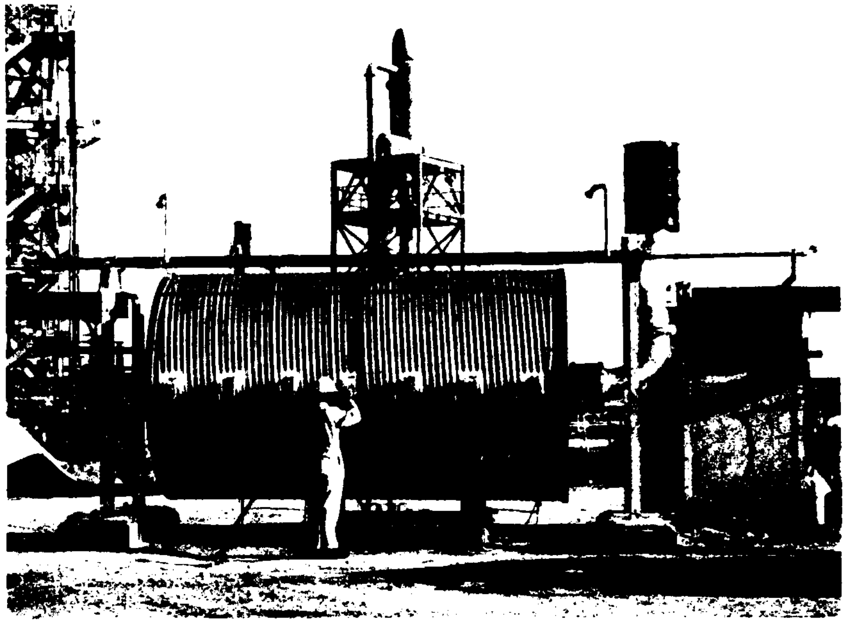


Figure [illegible]. Full-Scale Flame Test Chamber Installed on F-Stand

0.15 mm (0.006 in.) thick and banded into place, were used as frangible diaphragms to close the open chamber ends. This served two purposes: the dark environment enhanced motion picture photography of the flame front, and the closed chamber eliminated dispersion of the fuel-air mixture that might have been caused by local winds. Once the mixture in the chamber was ignited, the heat and increased pressure from the burning mixture blew out the diaphragms.

The interior surface of the chamber was painted flat black to aid photography. A glass viewing port near the upstream end of the chamber was used to take motion pictures of flame propagation. Reference light ports in the wall opposite the camera were used to indicate distances along the flame path. Instrumentation in the test chamber included four pressure sensors mounted, equispaced, in the wall along the horizontal center line. Seven flame sensors were originally mounted, equispaced, along the horizontal center line opposite the pressure sensors. However, early in the program, the flame sensors were relocated to the top center line of the chamber for a better viewing position of the stratified flame front. Five thermocouples were used to measure the temperatures within the chamber. Locations of the pressure, temperature, and flame sensors are shown in the schematic drawing Figure [illegible].

## HYDROGEN/AIR SPARK IGNITER

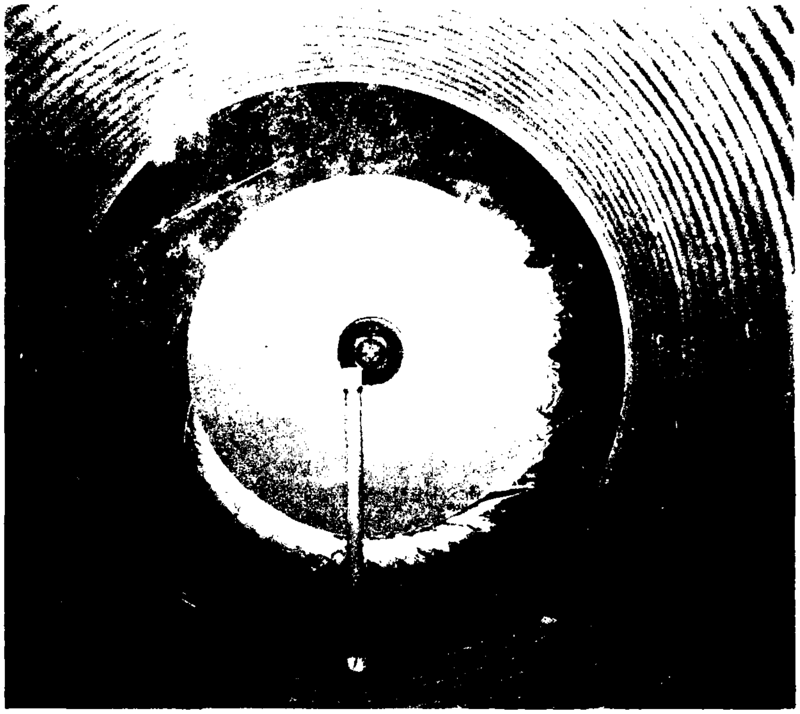
Ignition of the fuel/air mixture in the test chamber was accomplished with a hydrogen/air spark igniter. This igniter resembled a small rocket engine, where intersecting jets of hydrogen gas and air were ignited by a spark plug in the base of the combustion chamber. The resulting flame was directed vertically upward through a short nozzle for a nominal duration of [illegible] ms. The igniter assemblies were built into the end of a 1.1-m- (3.5-ft.-) long section of 5.[illegible]-cm- ([illegible]-in.-) diameter pipe mounted into fittings on the bottom of the test chamber. The point location of the ignition flame was just below the axial centerline of the chamber. There were three possible locations for the igniters: (1) upstream near the test arrester, (2) midchamber, and (3) downstream at the chamber exit. Only the upstream and downstream igniter position were used during the test program. When the downstream igniter position was used, the frangible diaphragm on the chamber exit was shielded from the flame by a sheet of aluminum covering approximately 40% of the total exit area. The aluminum shield delayed the rupture of this diaphragm until the flame had traversed the length of the chamber to reach the test arrester on the inlet end. This delay made it possible to obtain good quality motion pictures of the flame impinging on the arrester before the chamber was exposed to ambient light through the ruptured diaphragms. A photograph of the downstream igniter and flame shield are shown in Figure 3-6.

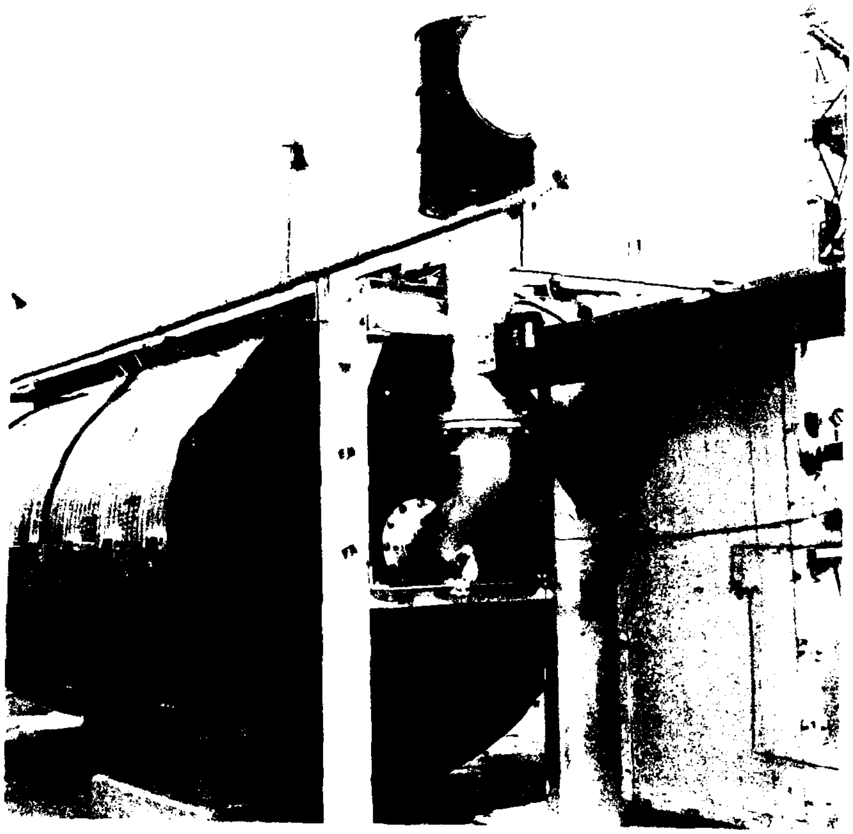
## EXHAUST-BURN STACK

An exhaust-burn stack was required for this test facility in compliance with air pollution regulations covering the controlled release of hydrocarbon vapors. This was accomplished by installing a 1.22-m (4-ft.) length of 30.5-cm (12-in. diameter piping on a vertically directed pipe elbow at the exit end of the flame chamber. The pipe contained a ducted fan and damper valve to control the exhaust flow, which, in turn, maintained atmospheric pressure in the test chamber prior to ignition. Spiral-wound, crimped metal ribbon arresters were attached to both ends of the exhaust stack assembly to prevent the propagation of flame into the piping. A gas sample rake was installed just downstream of the inlet flame arrester. The fuel/air mixture sample taken at this location was fed into an on-line total hydrocarbon analyser. The sample line was closed by a solenoid operated valve just prior to ignition to protect the analyser. At the top of the vertical stack, a shielded natural gas fired burner disposed of all combustible exhaust products. A photograph of the exhaust-burn stack assembly and the frangible diaphragm at the exit of the flame chamber is shown in Figure 3-7.

## SUSTAINED BURNING TEST FACILITY

The facility piping was modified after completion of the flame chamber testing to relocate the flame arrester test assembly out to an open area for the sustained burning tests. Two pipe elbows were inserted just upstream of the witness section to lower and turn the piping 90 deg away from the supporting structure. Another pipe elbow was inserted between the downstream end of the witness section and the arrester test assembly; this elbow directed the exhaust flow vertically as shown in Figure 3-8. The gas sample rake for the hydrocarbon analyser was inserted between the flanges upstream of the test section. Ignition was





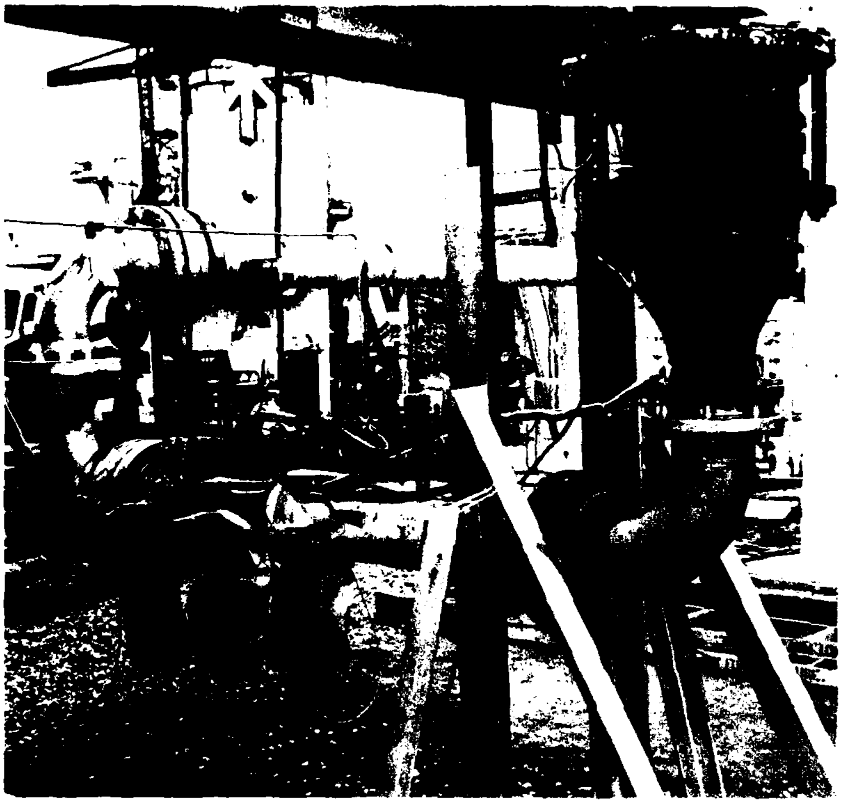


Figure [illegible]. [illegible]
[illegible]

## SECTION IV

## INSTRUMENTATION AND CONTROLS

### A. GENERAL DESCRIPTION

All instrumentation and controls at B-Stand facility were remotely operated and monitored. Test system parameters were measured at the test site using electrical transducers with their signals conducted to the blockhouse for conditioning, recording, and display. Location and identification of all principal instrumentation parameters and controls are shown in Figures 3-1 and 3-2. Table 4-1 is a listing of the nomenclature for all instrumentation and calculated parameters.

Test system parameters were divided into two groups: (1) steady-state (low-speed), and (2) transient-state (high-speed) data. Steady-state data includes all the measured and calculated parameters for the air system, fuel system, fuel vaporizer and condenser loop, fuel/air induction system, hydrocarbon analyzer, and the pre- and posttest pressure loss measured across the test arrester. Transient-state data includes the measured and calculated flame speeds and peak pressures developed in the test flame chamber and facility piping, and the success or failure of the experimental flame arrester.

Steady-state data was recorded and calculated on the JPL-developed Integrated Digital Acquisition and Controls System (IDAC) with back-up by the new Edwards Digital Acquisition and Control System (EDAC). Transient-state data was recorded on two high-frequency FM tape recorders and played back on an oscillograph at an expanded time scale. Flame speeds and peak pressures were manually scaled and calculated from the oscillograph traces. Flame speeds in the test chamber were also estimated from the high-speed motion picture films.

All critical control functions were either manually positioned on the controls console or automatically operated by the preset sequence timer. These operations were selectively recorded using electrical contact closures on IDAC, EDAC, FM tape, or a second high-speed oscillograph. Two strategically placed television (TV) cameras, with video displays in the blockhouse, monitored the fuels system area and the test flame chamber. Two high-speed motion picture cameras also recorded events both inside and outside the test flame chamber during the actual test firings. Visual coverage and controlled access to the test area were maintained by a safety monitor in an observation tower located over the blockhouse.

A detailed description of the instrumentation and controls system is given in Reference 2-10. Modifications and new additions that were made to the systems for this test program are described in the following paragraphs.

### B. STEADY-STATE DATA

The EDAC system is a new digital instrument recently installed at [illegible]. It was still in the process of functional checkout at the time of this program, so it was used as a backup steady-state data computing and recording system for the

[illegible]

| [illegible] | [illegible] | Description |
|---|---|---|
| [illegible] | kN/m² (psig) | Air flowmeter inlet pressure |
| [illegible] | kN/m² (psid) | Air flowmeter differential pressure |
| [illegible] | °C (°F) | Air flowmeter temperature |
| [illegible] | kN/m² (psig) | Fuel tank pressure |
| [illegible] | °C (°F) | Fuel tank temperature |
| [illegible] | kN/m² (psig) | Fuel tank dome loader pressure |
| [illegible] | kN/m² (psig) | Fuel line pressure |
| [illegible] | °C (°F) | Fuel line temperature |
| [illegible] | Hz (cps) | Fuel flowmeter frequency |
| [illegible] | kN/m² (psig) | Gaseous fuel pressure |
| [illegible] | kN/m² (psid) | Gaseous fuel differential pressure |
| [illegible] | °C (°F) | Gaseous fuel temperature |
| [illegible] | kN/m² (psig) | Fuel vaporizer outlet pressure |
| [illegible] | °C (°F) | Fuel vaporizer outlet temperature |
| [illegible] | °C (°F) | Fuel vaporizer core temperature |
| [illegible] | °C (°F) | Fuel injector inlet temperature |
| [illegible] | kN/m² (psig) | Fuel/air mixer outlet pressure |
| [illegible] | °C (°F) | Fuel/air mixer outlet temperature |
| [illegible] | °C (°F) | Fuel condenser inlet temperature |
| [illegible] | °C (°F) | Fuel condenser outlet temperature |
| [illegible] | °C (°F) | Coolant water inlet temperature |
| [illegible] | °C (°F) | Coolant water outlet temperature |
| PI | kN/m² (psig) | Inlet tee pressure |
| TI | °C (°F) | Inlet tee temperature |
| [illegible] | kN/m² (psig) | Inlet section pressure |
| [illegible] | kN/m² (psig) | Stabilizer section pressure |
| [illegible] | kN/m² (psig) | Witness section inlet pressure |
| [illegible] | kN/m² (psig) | Witness section center pressure |
| [illegible] | kN/m² (psig) | Witness section exit pressure |
| [illegible] | s (sec) | Inlet section flame sensor |
| [illegible] | s (sec) | Stabilizer section flame sensor |
| [illegible] | s (sec) | Witness section inlet flame sensor |
| [illegible] | s (sec) | Witness section center flame sensor |
| [illegible] | s (sec) | Witness section exit flame sensor |
| [illegible] | kN/m² (psid) | Flame chamber differential pressure, Sta. 1 |
| [illegible] | kN/m² (psid) | Flame chamber differential pressure, Sta. 3 |
| [illegible] | kN/m² (psid) | Flame chamber differential pressure, Sta. 5 |
| [illegible] | kN/m² (psid) | Flame chamber differential pressure, Sta. 7 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 1 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 2 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 3 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 4 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 5 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 6 |
| [illegible] | s (sec) | Flame chamber flame sensor, Sta. 7 |

Table 4-1. Instrumentation and Calculated Test Parameter Nomenclature (Continuation 1)

| Steady-State Parameters | Units, S.I. (Engr.) | Description |
|---|---|---|
| T74 | °C (°F) | Witness section exit temperature |
| T81 | °C (°F) | Test arrester inlet temperature |
| TIU | °C (°F) | Upstream igniter flame temperature |
| TID | °C (°F) | Downstream igniter flame temperature |
| TCR | °C (°F) | Flame chamber roof temperature |
| TCL | °C (°F) | Flame chamber lower temperature |
| TCM | °C (°F) | Flame chamber metal temperature |
| T91 | °C (°F) | Exhaust stack inlet temperature |
| T92 | °C (°F) | Exhaust stack exit temperature |
| HCA | % | Exhaust stack total hydrocarbon analysis |
| PA1 | $kN/m^2$ (psig) | Test arrester inlet pressure |
| DPA1 | $kN/m^2$ (psid) | Test arrester differential pressure-pretest |
| DPA2 | $kN/m^2$ (psid) | Test arrester differential pressure-posttest |
| PAMB | $kN/m^2$ (psia) | Test area ambient pressure |

| Calculated Parameters | Units, S.I. (Engr.) | Description |
|---|---|---|
| MA | kg/h (lb/h) | Air mass flow |
| MF | kg/h (lb/h) | Liquid fuel mass flow |
| A/F | ratio | Air mass flow to liquid fuel mass flow ratio |
| MFG | kg/h (lb/h) | Gaseous fuel mass flow |
| A/FG | ratio | Air mass flow to gaseous fuel mass flow ratio |
| $\phi$ | ratio | Equivalence ratio |
| VA | m/s (ft/sec) | Air flow velocity through 15.2-cm (6.0-in.-) diameter pipe |
| FXX-FYY | m/s (ft/sec) | Average flame speed between two adjacent flame sensors |
| SX-SY | m/s (ft/sec) | Average flame speed between two adjacent light ports or a light port and the test arrester obtained from the motion pictures |

[illegible] computer, which it will eventually replace. The heart of the EDAC is a [illegible] computer. It has a maximum recording rate up to 20,000 [illegible] per second. At this time only 200 channels are assigned to the [illegible] facility.

[illegible] calibration sequence, EDAC records the counts each calibration [illegible] and then uses these counts, along with the appropriate [illegible] equation, to calculate the engineering units for each parameter. The computer also performs calculations such as averaging, polynomials, [illegible] operations involving two or more input channels. Other [illegible] capabilities include totalizers, period counters, parallel data, and [illegible] time tagged to the nearest millisecond.

EDAC outputs data on magnetic tape, line printers, and video monitors. The magnetic tapes are used for record storage, from which posttest playbacks of input parameters and calculations are made to the line printer. The line printer records 10 parameters with channel identification, engineering units, and time. The [illegible] is programmable for maximum output at points of interest. The video units provide on-line real-time displays of up to 10 parameters with channel identification, engineering units, and contact closure status. These displays can be selected from 6 preprogrammed pages. High and low limits can be assigned to input parameters. The limit output signal is capable of operating control circuits or sounding alarms within 10 milliseconds of exceeding a limit.

Simultaneous steady-state data from both the IDAC and EDAC systems were very comparable, although not exactly alike. This discrepancy is reportedly caused by a small difference in the time base for computer calculation between the two systems that cannot be resolved. The EDAC system when totally operational will replace IDAC as the primary data system for follow-on programs.

## [illegible]. TRANSIENT-STATE DATA

New flame sensors that could withstand repeated exposure to ambient light and still remain sensitive to the light-blue color of hydrocarbon flame had to be assembled for the flashback flame chamber. The Du Mont Type 6291 photomultiplier tubes used as flame sensors in the facility piping were not suitable because the phosphorescent coating on the detector can be deteriorated by bright sunlight. Photovoltaic type detectors, similar to those reported in References [illegible], which do not have this sensitivity, were used instead. They are the EG and G [illegible] silicon photovoltaic detectors that have a spectral range from [illegible] Å ([illegible] to 1150 Nm) with a maximum response at 9000 Å (900 Nm) and a responsivity of [illegible] × 10 [illegible] volts/watt. Operational amplifiers were built to the [illegible] and circuitry suggested by EG and G. The detector and amplifier were [illegible] in a weather-tight aluminum box with a phototube viewing port [illegible] front collimating slot. The distance from the collimating [illegible] to the detector could be varied to optimize the viewing angle and detector [illegible]. Although the rise-time response of the photovoltaic detector is somewhat slower than the photomultiplier tube, 1.5 microseconds compared to [illegible], it is more than adequate for detecting the expanding atmospheric [illegible] in the flame chamber.

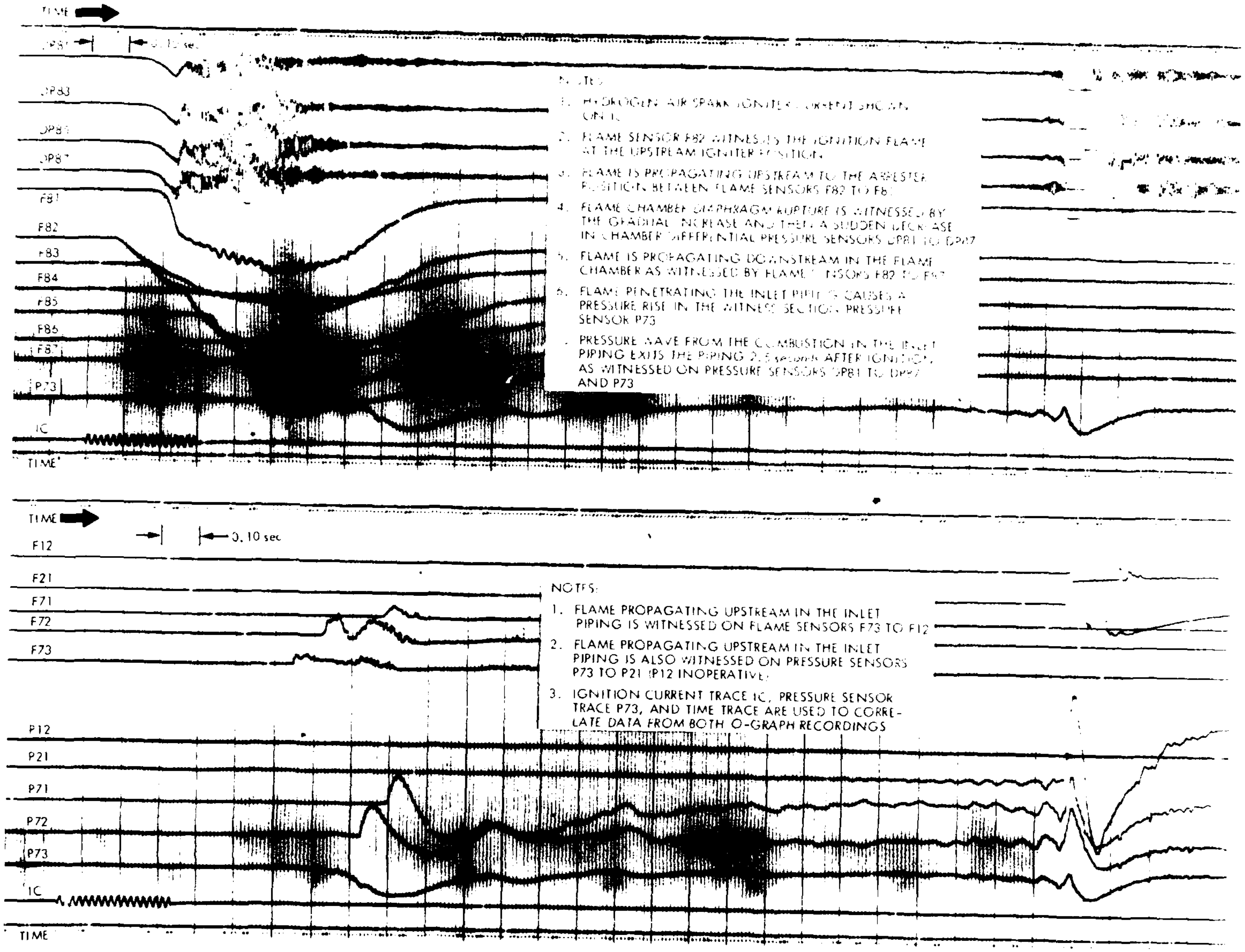
Seven photovoltaic flame sensors were initially installed at [illegible]-m ([illegible]-ft) intervals along the horizontal centerline of the flame chamber. They were later relocated to the chamber top centerline when motion pictures of flame propagation showed the flame illumination intensity varying unpredictably from top to bottom in the chamber. It is believed this is caused by gravitational stratification of the fuel/air mixture after it leaves the facility piping. The flame detector's overhead view, looking down into the propagating flame front, resulted in more reliable flame speed measurements.

Flame chamber peak pressure rise was measured with four Statham Model [illegible] differential pressure-type transducers mounted at 1.22-m (4-ft) intervals along the horizontal centerline of the chamber. It was intended that these pressure sensors measure the pressure rise at the chamber wall during the passage of the flame front. In actual practice, they simultaneously sensed the rise in chamber pressure from the spherically expanding ball of flame up to the point of chamber diaphragm rupture. The resulting resonance from this pressure spike in the chamber masked any evidence of flame passage past the individual pressure sensors.

Three flame sensors and three pressure sensors mounted at 0.31-m (1-ft) intervals on opposite sides of the witness section piping were used to record flashback flame penetration through the test arresters. Two of these flame sensors were a photomultiplier tube type and one was a photovoltaic type. The pressure sensors were all quartz-crystal piezoelectric-type transducers flush-mounted to the inside wall. In addition, there was a similar combination of flame sensor and pressure sensor in both the inlet igniter section and stabilizer section of the facility piping to record flame propagation up to these locations. An inlet flame arrester stopped any further flame penetration beyond this point into the induction system piping.

The signals from all flame sensors and pressure sensors located in the flame chamber and facility piping were recorded on two high-frequency FM tape recorders and the on-line oscillograph. A 100-Hz coded time pulse and the spark igniter current were also recorded and used as reference points for test initiation and time correlation between the various recorders. A typical example of transient-state data for the flame chamber sensors recorded on the FM tape and playback on an oscillograph with an expanded time base is shown in Figure 4-1.

The [illegible] system was used as the principal recorder for the thermal soak-back data measured by thermocouples installed on the flame arresters during sustained burning tests. Recorded at millisecond scan intervals, the data was time edited, played back, and printed at time intervals ranging from 5 to 120 seconds, depending on the length of test and the transient-state of the data. Video displays of this real-time flame arrester temperature data were monitored during the test to identify flame penetration. This was later confirmed by data from the flame sensors and pressure sensors in the witness section piping that was recorded on FM magnetic tape and played back on the oscillograph.


TIME
DP81
0.10 sec
DP83
DP85
DP87
F81
F82
F83
F84
F85
F86
F87
P73
IC
TIME
NOTES:
1. HYDROGEN-AIR SPARK IGNITER CURRENT SHOWN ON IC
2. FLAME SENSOR F82 WITNESSES THE IGNITION FLAME AT THE UPSTREAM IGNITER POSITION
3. FLAME IS PROPAGATING UPSTREAM TO THE ARRESTER POSITION BETWEEN FLAME SENSORS F82 TO F81
4. FLAME CHAMBER DIAPHRAGM RUPTURE IS WITNESSED BY THE GRADUAL INCREASE AND THEN A SUDDEN DECREASE IN CHAMBER DIFFERENTIAL PRESSURE SENSORS DP81 TO DP87
5. FLAME IS PROPAGATING DOWNSTREAM IN THE FLAME CHAMBER AS WITNESSED BY FLAME SENSORS F82 TO F87
6. FLAME PENETRATING THE INLET PIPING CAUSES A PRESSURE RISE IN THE WITNESS SECTION PRESSURE SENSOR P73
7. PRESSURE WAVE FROM THE COMBUSTION IN THE INLET PIPING EXITS THE PIPING 2.5 seconds AFTER IGNITION AS WITNESSED ON PRESSURE SENSORS DP81 TO DP87 AND P73
TIME
F12
0.10 sec
F21
F71
F72
F73
NOTES:
1. FLAME PROPAGATING UPSTREAM IN THE INLET PIPING IS WITNESSED ON FLAME SENSORS F73 TO F12
2. FLAME PROPAGATING UPSTREAM IN THE INLET PIPING IS ALSO WITNESSED ON PRESSURE SENSORS P73 TO P21 (P12 INOPERATIVE)
3. IGNITION CURRENT TRACE IC, PRESSURE SENSOR TRACE P73, AND TIME TRACE ARE USED TO CORRELATE DATA FROM BOTH O-GRAPH RECORDINGS
P12
P21
P71
P72
P73
IC
TIME

## D. GAS-SAMPLE ANALYSIS SYSTEM

The gas-sample analysis system used for this program is described in detail in Reference 2-10. Briefly, it is an on-line system that utilizes a Beckman Model 400 Total Hydrocarbon Analyser instrument combined with a JPL designed and fabricated air dilution and calibration system. The analyser automatically and continuously measures the concentration of hydrocarbon in a flowing gas sample, utilizing the flame ionization method of detection. It was calibrated using propane ($C_3H_8$) and air mixtures. To analyse other hydrocarbon fuel and air mixtures, the number of carbon atoms per molecule of fuel had to be in a ratio to that of propane. A flow system schematic drawing of the complete gas-sample analysis system is shown in Figure 4-2. A listing of the fuels and their properties that are used in this program is given in Tables 2-1 and 2-2.

The hydrocarbon gas analyser was located as close to the test flame chamber as practical to minimize response time. It was placed in a steel-walled protective enclosure adjacent to the exhaust-burn stack. The gas sample rake was installed in the inlet elbow of the exhaust-burn stack. A three-way solenoid valve provided a gaseous nitrogen purge through the sample rake when not in use. Analyser response time after activation of the three-way sample valve was approximately 30 seconds. Figure 3-7 is a photograph of the protective enclosure housing the gas analyser located next to the exhaust-burn stack.

## E. PHOTOGRAPHIC DATA

Two motion picture cameras were used to record every test firing. One camera was positioned outside the flame chamber with a view of the entire test section assembly. Operating at 32 frames per second, this camera recorded the rupture of the flame chamber diaphragms and the extent of the emitted flame plume. The other camera was positioned adjacent to the flame chamber observation window with a view of the inside of the chamber, including the upstream igniter and the downstream face of the test arrester. Figure 4-3 is a photograph of this camera installation. Operating at 100 frames per second, it was possible with this camera to record the propagating flame front inside the chamber. Four light ports, equally spaced on the opposite wall, provided reference points for determining distance traveled. A schematic drawing of the flame-chamber camera installation is shown in Figure 4-4. The distances traveled by an expanding spherical flame, when viewed by the camera, are indicated between each adjacent light port, and from the light port in line with the igniter to the face of each of the four flame arrester test assemblies. By counting the number of motion picture frames required for the flame front to traverse these known path lengths, the lapse time was estimated and the average flame speed was calculated. The flame speeds obtained by this method will not necessarily agree with those calculated from the flame sensor data, because of the different sight locations and viewing angles, but they are of the same order of magnitude. Figure 4-5 is a selected series of six photographs taken from test motion picture film showing a toluene air flame propagation from ignition to sustention on the downstream face of the dual 20-mesh screens arrester. Figure 4-6 is a similar series of photographs showing a toluene/air flame propagation from ignition to penetration into the open ended facility piping, causing an eruption of flame from the pipe.

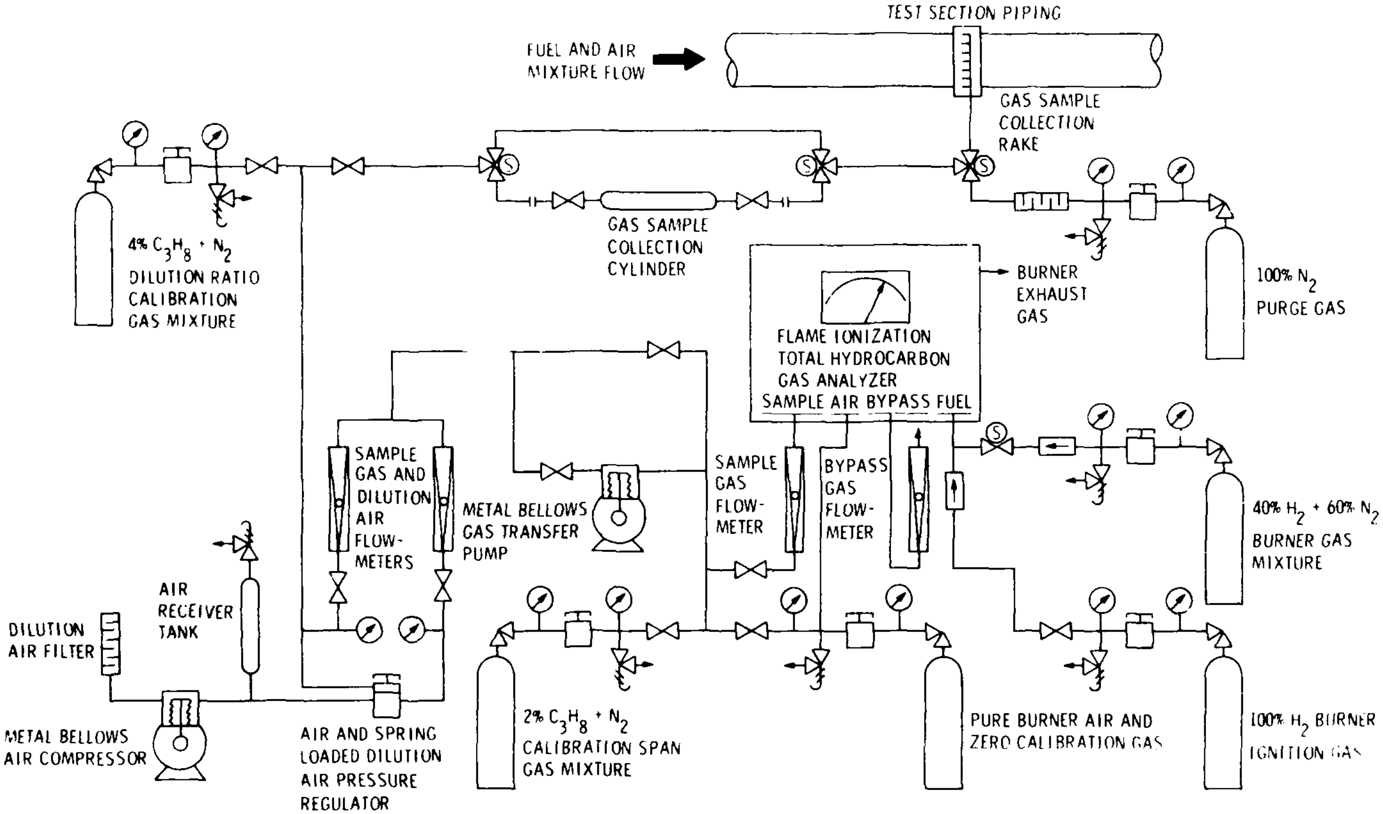



Figure 4-2. Hydrocarbon Gas Sample Analyzer and Air Dilution Flow System Schematic Diagram

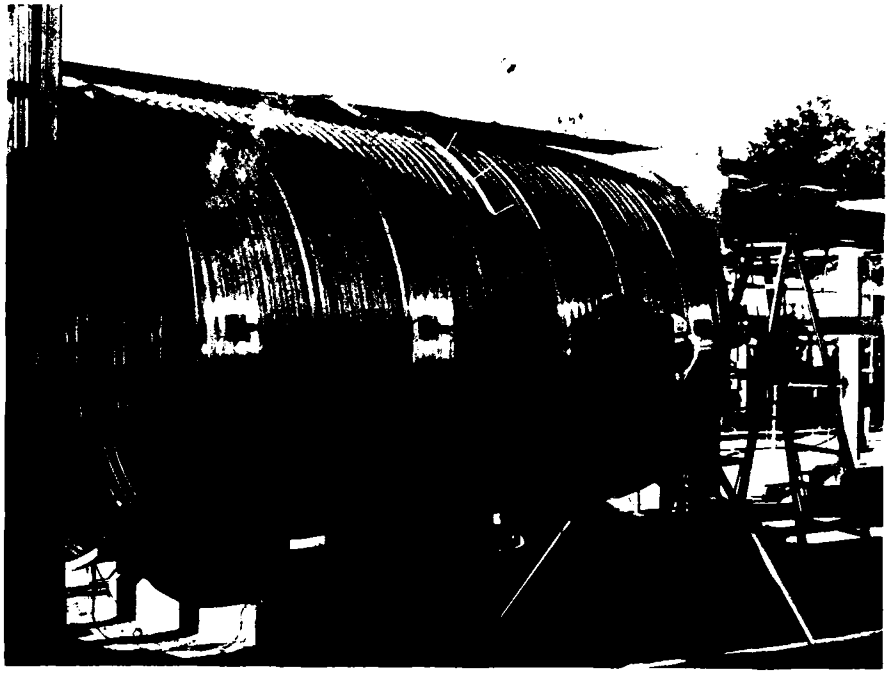


Figure [illegible]. [illegible] Installation

F. [illegible]

The [illegible] system was the primary source for steady-state data, with back-up by the [illegible] system. [illegible] computer capability that converts input data to engineering units, and output to printers and video monitors. Special [illegible] and [illegible] software programs were written for air and fuel systems data to calculate air-mass flow, fuel-mass flow, air-to-fuel ratio, and equivalence ratio. To assure maximum accuracy from the instrumentation systems, an end-to-end calibration was [illegible]. A detailed description of the instrumentation systems, calibration methods, and the determination of uncertainty for measured and calculated parameters is presented in Reference [illegible]. The following is a summary of the [illegible] steady-state data uncertainties secured with a [illegible] probability.

(a) Uncertainty of pressure measurement is ± [illegible] of transducer full-scale range.

(b) Uncertainty of differential pressure measurement is ± [illegible] of transducer full-scale range.

(c) Uncertainty of temperature measurement in percent of reading is:

[illegible] = ± [illegible]

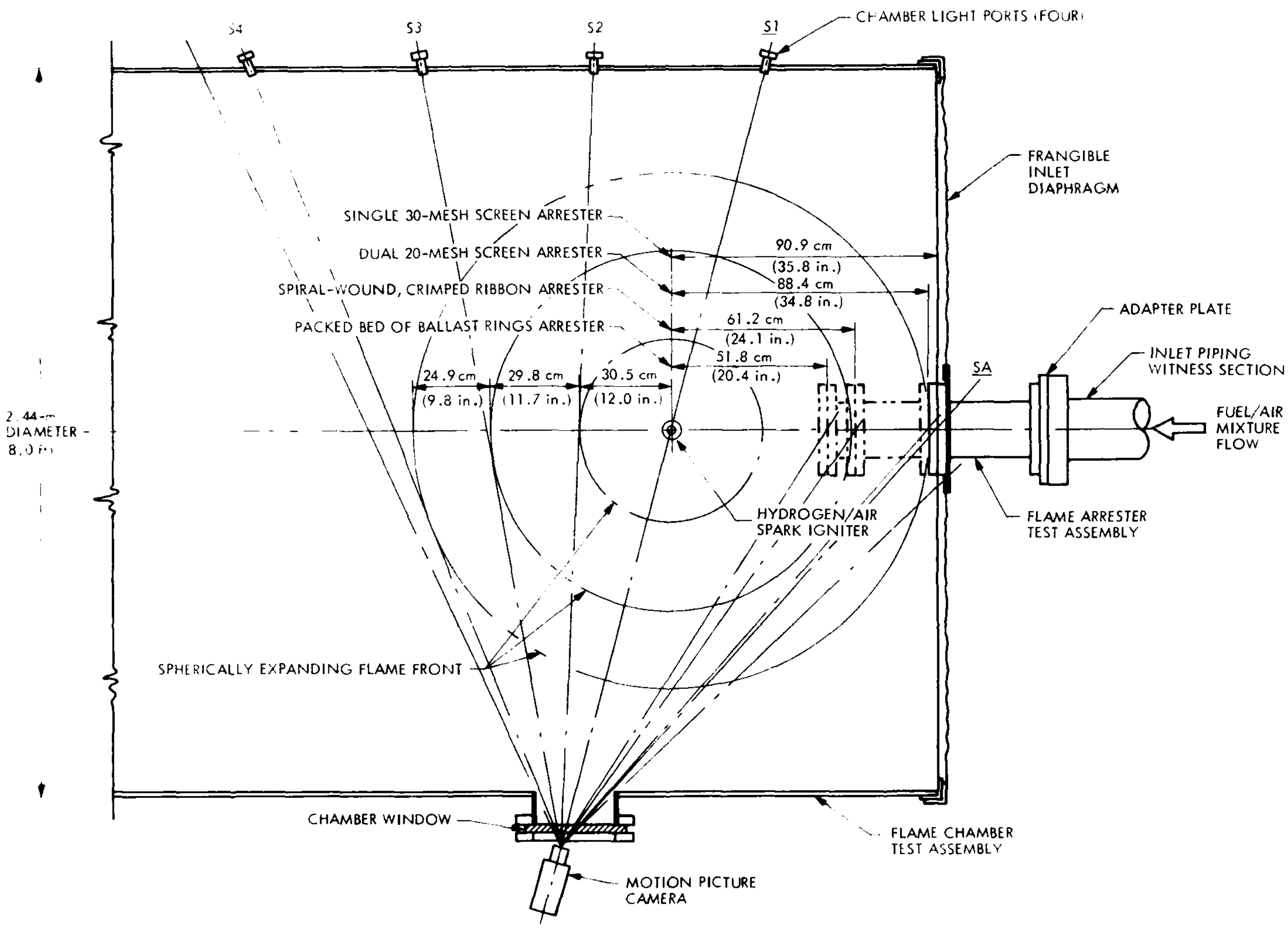
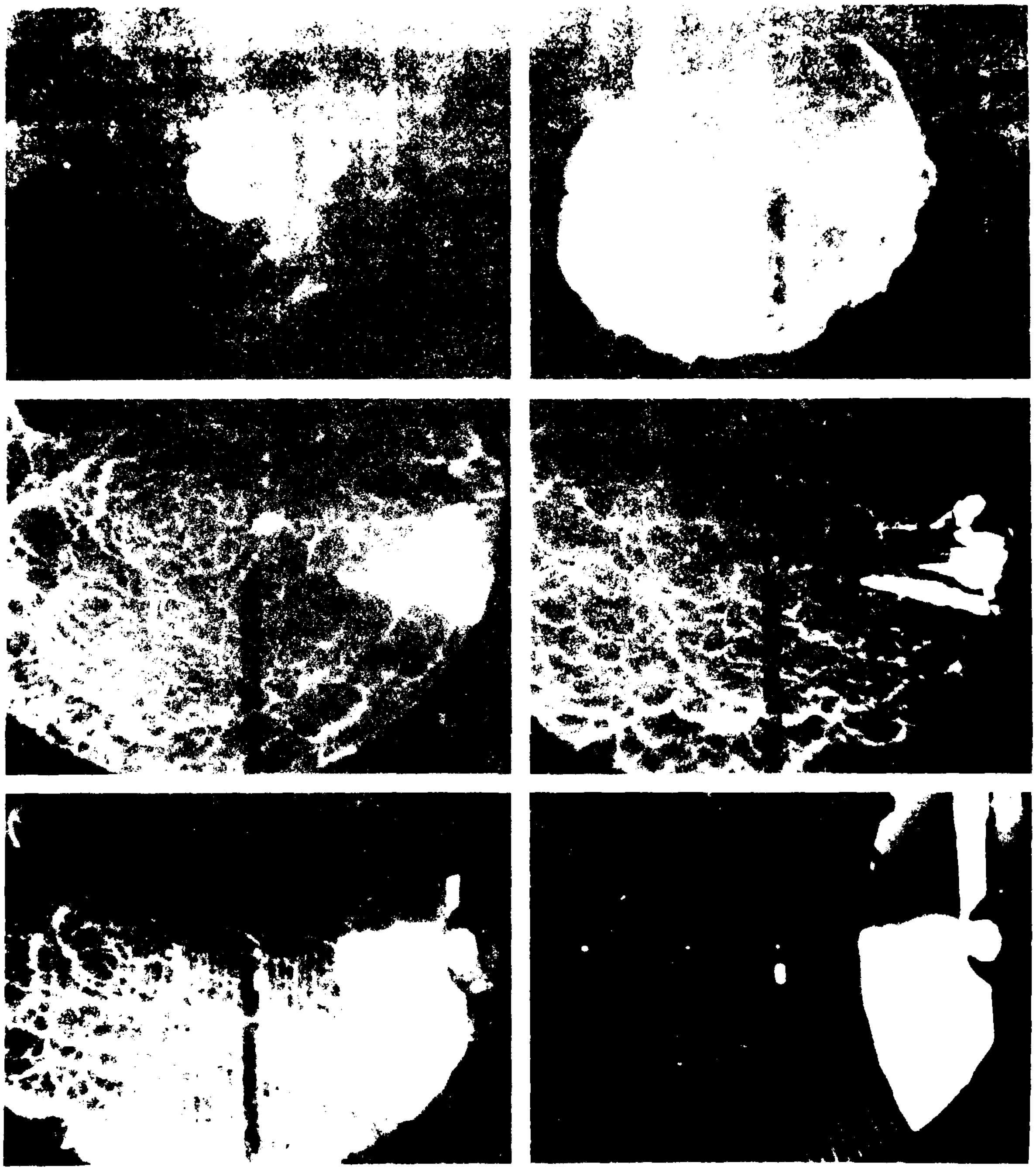
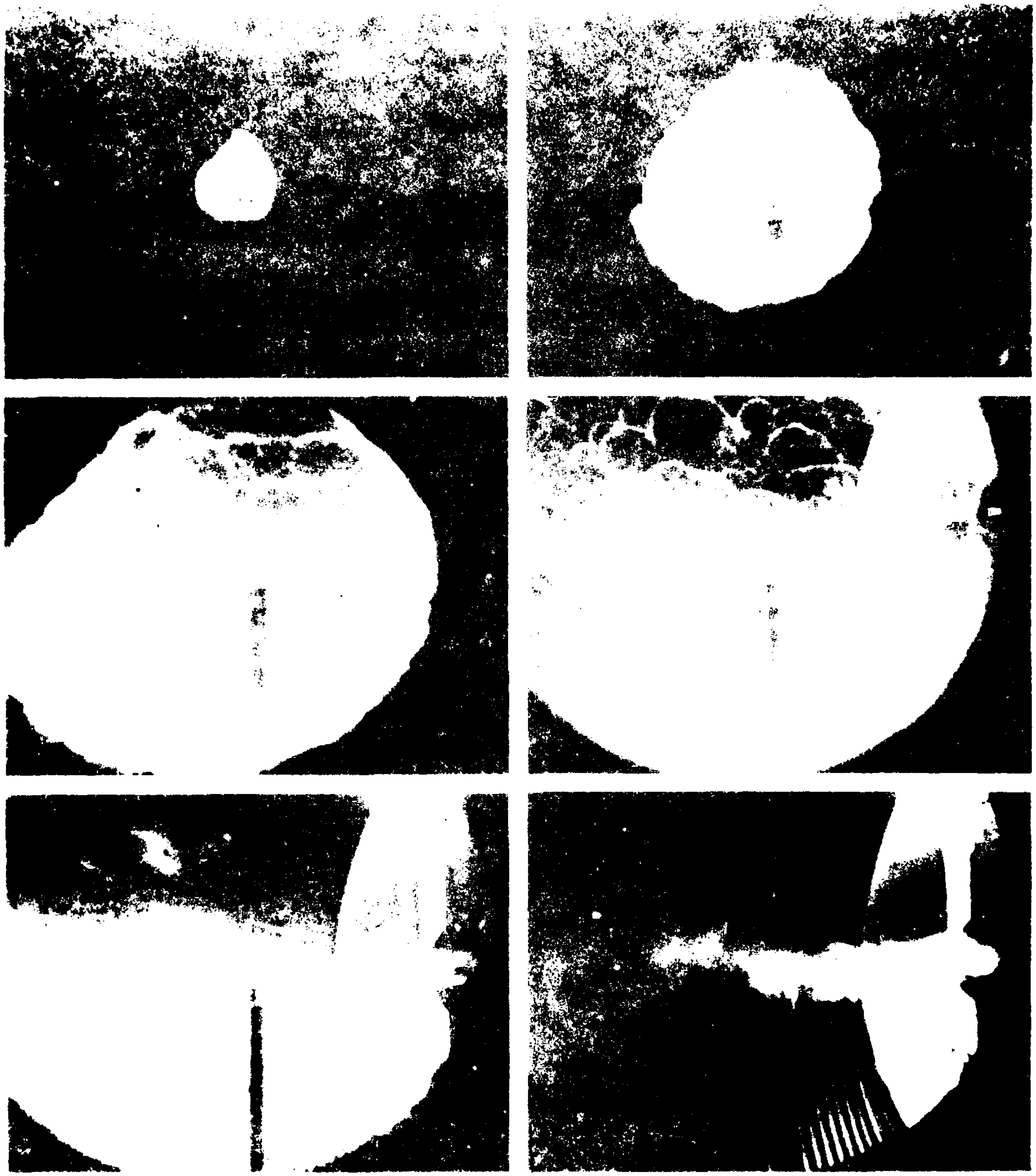



Figure 4-4. Schematic Drawing of Flame Test Chamber Motion Picture Camera Installation





(b) 37.8 to 93.3°C (100 to 200°F) = ± 1.4%
(c) 93.7 to 148.9°C (200 to 300°F) = ± 0.85%
(d) 148.9 to 204.4°C (300 to 400°F) = ± 0.65%
(e) 204.4 to 276.7°C (400 to 530°F) = ± 0.49%
(f) 276.7 to 1260°C (530 to 2300°F) = ± 0.43%

(4) Uncertainty for air-velocty or air-mass-flow calculations is ±1.82% of value.

(5) Uncertainty for liquid-fuel-mass-flow calculation is ±1.93% of value.

(6) Uncertainty for gaseous-fuel-mass-flow calculation is ±2.88% of value.

(7) Uncertainty for calculated air-to-liquid-fuel mixture ratio and equivalence ratio is ±2.65% of value.

(8) Uncertainty for calculated air-to-gaseous-fuel mixture ratio and equivalence ratio is ±3.41%.

Using the uncertainties listed above, the maximum uncertainty that can be expected for the measured and calculated steady-state test parameters associated with the average value at standard test conditions are listed in Table 4-2.

The transient-state data were recorded on an Ampex Model FR 2200 and an Ampex Model FR 3020 high-frequency FM tape recorders. Photovoltaic detector flame sensors were the primary instruments used to determine flame speeds. Strain-gauge-type differential pressure transducers were the primary instruments used to measure peak pressure rise in the flame chamber. Flame sensor and pressure sensor test data, along with pre- and posttest calibrations recorded on the FM tapes, were played back on an oscillograph at an expanded time base. The following is an analysis of the uncertainties associated with transient-state data assured with a 95% ($2\sigma$) probability.

(1) The uncertainty of flame chamber peak-pressure rise measurement is ±5.85% of transducer range.

(2) The uncertainty of calculated flame sensor flame speed measurement is ±5.45% of value.

(3) The uncertainty of calculated photographic flame speed measurement is ±10.07% of value.

The maximum uncertainty that can be expected for measured and calculated parameters associated with the averaged values of flashback flame speed and peak pressure rise in the test flame chamber at standard test conditions are listed in Table 4-2.

Table 4-[illegible]. Maximum Uncertainty for Measured and Calculated Parameters at the Standard Test Condition

| Parameter | Symbol | Uncertainty |
|---|---|---|
| Steady-State Data | | |
| Air flowmeter inlet pressure | PBO | ±0.27 kN/m$^2$ (±[illegible].039 psi[illegible]) |
| Air flowmeter differential pressure | DPO | ±0.0083 kN/m$^2$ (±0.00[illegible] [illegible]) |
| Air flowmeter exit temperature | TO1 | ±1.3°C (±2.8°F) |
| Liquid fuel line pressure | PFL | ±14.0 kN/m$^2$ (±[illegible].0 psi[illegible]) |
| Liquid fuel line temperature | TFL | ±0.9°C (±2.7°F) |
| Liquid fuel flowmeter frequency | FMF | ±0.8 Hz |
| Gaseous fuel line pressure | PGF | ±17.2 kN/m$^2$ (±[illegible].50 psig) |
| Gaseous fuel line temperature | TGF | ±0.9°C (±2.7°F) |
| Flame arrester inlet pressure | PA1 | ±0.269 kN/m$^2$ (±0.0[illegible]9 psig) |
| Flame arrester differential pressure | DPA | ±8.3 N/m$^2$ (±0.0012 psid) |
| Test area ambient pressure | PAMB | ±0.538 kN/m$^2$ (±0.078 psia) |
| Air-mass flow | MA | ±1.90 kg/h (±4.19 lb/h) |
| Air velocity | VA | ±0.083 m/s (±0.27 ft/s) |
| Liquid-fuel-mass flow | MF | ±0.158 kg/h (±0.35 lb/h) |
| Air to liquid-fuel-mass ratio | A/F | ±0.35 |
| Gaseous-fuel-mass flow | MFG | ±0.240 kg/h (±0.529 lb/h) |
| Air to gaseous-fuel-mass ratio | A/FG | ±0.44 |
| Equivalence ratio | $\phi$ | ±0.04 |
| Transient-State Data | | |
| Flame chamber peak pressure rise | DPXX | ±121 N/m$^2$ (±0.0176 psid) |
| Flame sensor flame speed | FXX-FYY | ±0.19 m/s (±0.63 ft/s) |
| Photographic flame speed | SX-SY | ±0.35 m/s (±1.16 ft/s) |

SECTION V

TEST OPERATING PROCEDURES

A. GENERAL SAFETY REQUIREMENTS

All test operating procedures involving fuel transfer, or performed with the fuel system pressurized, required the safety tower operator to be in position, monitor all communication on a headset, and control access to the test area with the safety status lights. The test stand was normally in a GREEN condition, which permitted open access to all personnel. Fuel transfers and test preparations were performed in an AMBER condition, which restricted nonoperating personnel to the workshop area, unless permission was granted to enter other areas. A RED condition, which isolated the test stand and the surrounding designated area from all personnel, was used during actual test.

A minimum of two men was required at the site during fuel transfers and test preparations. Personnel safety equipment included hard hats, face shields, gloves, fire retardant coveralls, and for some fuels, breathing air systems. Additional safety equipment was available including safety showers, eye washes, and the Firex water deluge system. All operations, except the replacement of the flame chamber diaphragms and the changing of the test flame arrester, were performed using formal procedures in the form of check lists, with individual pages dated and timed, and with each step initialed by two persons witnessing the event.

An ignition-completion key switch, which prevented the actuation of the hydrogen/air spark igniter except during checkouts and test operations, was located at the test stand.

B. OPERATING PROCEDURE CHECK LISTS

The following is a description of the operating procedures and check lists used in the flashback flame tests.

1. Pretest System Checkouts

a. Preliminary Check. This check confirmed proper installation of the test item, instrumentation and control cable connections, readiness of the nitrogen pressurant and purge system, selection of the proper fuel supply mode, requested photographic coverage, and that the safety system was operational.

b. Electromechanical Checkouts. These checks examined, at the test stand, the overall control system readiness by individual confirmation of proper operation of each control in the blockhouse.

c. Sequence Timer/Emergency Circuit Checkout. This checkout operated the preset automatic sequence timer, without actual fuel flow, while recording control-element actuations on the facility oscillograph. Sequence times of the various elements were measured and adjusted where necessary. The sequence was then repeated, adding a shutdown with the emergency switch to confirm proper emergency switch actuations.

d. Leak Check. These checks provided a gaseous nitrogen system leak check at maximum operating pressure for the fuel system, fuel vaporizer and condenser loop, fuel induction system, and the air compressor system.

NOTE: The four checklist procedures described above were not performed before each test, but were done when special circumstances, such as component changes, malfunctions, or severe weather, were encountered.

2. Fuel Transfer Procedures

a. Propellant (fuel) Fill Check Lists. These procedures were provided for transferring liquid fuels from their storage containers into the test stand fuel supply tank. Propane and butane were transferred via their own vapor pressure. The other liquid fuels were transferred from drums by means of an air-motor-driven pump. It was common to expect up to five separate tests in a day, each of which required approximately $4.6 \times 10^{-3}$ $m^3$ (1 gal) of fuel. Therefore, the fuel supply tank was topped off for each test day. The gaseous fuel system was loaded by simply connecting new pressurized gas cylinders to the supply manifold.

b. Propellant (fuel) Offload. These transfers from the fuel supply tank were normally returned to the appropriate storage container. Small quantities of propane or butane could also be disposed of through the burn stack. Generally, fuels from the vaporizer/condenser loop remaining in the collector tank were not suitable for recycling and were disposed of as waste. It was necessary to empty the collector tank after every two days of testing.

3. Test Preparations

The Test Preparations Check Lists for instrumentation and test systems were completed concurrently on the day of testing. In the blockhouse, all patchboard connections were completed and instrumentation was setup. An end-to-end instrumentation system calibration was performed. At the test stand, various safety check and facility setups were made: condenser cooling water was turned on, the hydrocarbon analyzer was put in operation, and the hydrogen and air gas pressures were adjusted for the igniter. At the control console, the air compressor was started and the air flow adjusted by means of the air metering valve and the air bypass valve. After the air system temperature and flow were stabilized at the desired values, the test flame arrester pretest pressure loss was measured and recorded.

The fuel vaporizer heater was activated, and nitrogen purge gas flowed through the heater coils and into the condenser for the preheat cycle. The test stand safety condition was changed from GREEN to AMBER. The fuel supply tank was pressurized with nitrogen up to the desired operating pressure. The vaporizer heater nitrogen purge gas was turned off and fuel flow was metered at a low level. The fuel flow was increased up to the desired test condition as the vaporizer heater reached the operating temperature.

Final visual checks were made of the test stand area, and the ignition completion key switch was turned on. All operating personnel evacuated the test stand area and its safety condition was changed to RED.

4. Blockhouse Preparation

Blockhouse preparation began with a weather station confirmation of wind velocity and direction and the local barometric pressure. Control console circuits for ignition and emergency shutdown functions were armed and each significant panel switch and its position confirmed. With all test personnel at their operating positions, the test conditions were reviewed and confirmed. A pretest instrumentation calibration was recorded and the countdown procedure was begun.

5. Countdown

A typical "countdown" procedure follows:

(1) An announcement was made over the public address system to alert personnel in the general area that a detonation may occur. Generally, the detonation noise was very intense and sharp, capable of creating an indirect hazard. A horn signal was also sounded.

(2) The IDAC tape, EDAC tape, printer, and oscillograph were turned ON to a SLOW SPEED.

(3) The hydrocarbon analyzer purge was turned OFF, allowing the analyzer to sample the fuel/air mixture flowing through the exhaust-burn stack.

(4) The fuel mixer valve was changed to the RUN position, allowing fuel to flow to the test piping for the first time in the test sequence. The burn-stack-purge valve was opened to sweep out combustible gases from the collector tank vent line. The oscillograph was turned OFF.

(5) As the fuel/air mixture traveled through the facility piping and into the flame chamber, the hydrocarbon analyzer responded with a steadily increasing signal. The countdown timer was then stopped for a HOLD period, while fuel flow and air flow were confirmed or adjusted, if necessary. During flame chamber testing, the time required for the mixture ratio of chamber exhaust gas to reach the desired level ranged from 2 to 27 minutes due to differences in chamber temperature, fuel density, and flow-through characteristics in the test chamber.

(6) When the COUNTDOWN resumed, the IDAC tape, EDAC tape, and printer were switched to CONTINUOUS MODE and the oscillograph and movie camera were turned ON. The vaporizer heater was turned OFF (flame chamber tests only) to prevent electrical switching noise on the data traces during the test. The high-frequency FM tape recorder was turned ON.

(7) The hydrocarbon analyzer purge was turned ON, again isolating it from the test system to protect it from possible pressure pulse damage.

(8) Valves were actuated to the CLOSED position to isolate the low-pressure transducer from possible pressure pulse damage.

The igniter was ARMED by a toggle switch and the oscillograph was switched to HIGH SPEED.

The sequence timer was turned ON. This caused the igniter to fire for 300 ms. For flame chamber tests, the hydrogen and air valves for the igniter were opened and the transformer energizing the spark plug was powered simultaneously. Actual duration of the flame was 150 to 200 ms. For sustained burning tests, only the transformer energizing the spark plug of the igniter was powered for 300 ms.

At the end of the desired test time, the test was terminated by operating the EMERGENCY CUTOFF switch. For flame chamber tests, this occurred five seconds after ignition. For sustained burning tests, this occurred thirty minutes after ignition or when flame penetration occurred. The EMERGENCY CUTOFF switch triggered the following events: fuel mixer valve was switched from RUN to CONDENSE position, vaporizer purge was turned ON, vaporizer heater was turned OFF (sustained burning tests only), fuel tank outlet valve (liquid) was CLOSED, and fuel cylinder outlet valve (gaseous) was CLOSED.

The igniter was UNARMED, the oscillograph changed to LOW SPEED, and the high-frequency tape turned OFF.

The fuel metering valve was CLOSED and the movie camera was turned OFF.

Fuel supply tank pressure transducers were vented and a posttest calibrate was performed on the instrumentation.

(15) Fuel supply tank pressure transducers and the test arrester pressure transducers were reopened to the test system and all instrumentation was turned OFF.

(16) Compressor air flow was maintained to purge residual fuel and combustion by-products from the test piping.

## Posttest

The posttest procedure included a visual inspection of the test stand. The test stand safety condition was changed to AMBER. Reentering personnel inspected the rupture disc assemblies, and replaced discs as required. The posttest flame arrester pressure loss was measured and recorded. Chamber diaphragms were replaced for repeats of flame chamber tests.

If a repeat test was to be made, the hydrocarbon analyzer was checked out. The test preparation Procedure would then be restarted from the point of turning on the air compressor.

Following the last test of the day, posttest end-to-end calibration of the instrumentation system was made. Fuel in the induction system was pushed back to the supply tank and the system thoroughly purged with nitrogen gas.

Immediately after each test, the data recorded on the FM tape recorder was played back onto a quick-look oscillograph at an expanded time scale of 8 to 1. This data told the test conductor that he did or did not get ignition, that the flame arrester quenched the flame, or that the flame penetrated through. If the flame arrester was penetrated and the flame speed was high, a playback record was made of the FM tape data at an expanded time scale of 32 to 1 for greater resolution. These records were then analyzed to determine flame speeds and peak pressure rise data.

## SECTION VI

## FACILITY CHECKOUT TESTS

### A. SUBSCALE FLAME CHAMBER TESTS

A series of tests were made to check out facility systems installed specifically for the flashback flame tests. The initial tests were made in a subscale flame chamber while the full-scale chamber was being fabricated. These tests were conducted to evaluate the new hydrogen/air spark igniter system, the operating procedures required to fill an enlarged chamber with a combustible fuel air mixture that could be verified with measurements on the total hydrocarbon analyser, the effectiveness of the frangible plastic chamber diaphragms, and, finally, the extent and nature of the problems associated with the flame plume emitted from both ends of the test chamber following the diaphragm rupture.

The subscale chamber shown in Figure 6-1 was made from an existing piece of steel pipe 0.91 m (3 ft.) in diameter and 2.13 m (7 ft.) long. It was mounted on supports at the exit end of the facility piping. A commercial Pres-Vac screen-flame arrester housing was installed downstream of the witness section for these check-out tests. Frangible diaphragms made from 6-mil-thick black polyethylene plastic sheeting covered both ends of the chamber. A nominal 15.2-cm- (6-in.-) diameter hole in the upstream diaphragm provided entrance for the fuel/air mixture, and a nominal 7.6-cm- (3-in.-) diameter hole in the downstream diaphragm provided the exhaust exit. The gas sampling probe for the hydrocarbon analyser was positioned at the center of the downstream hole. The hydrogen/air spark igniter was mounted on a length of pipe in the center of the chamber, such that the point of ignition was at the axial center line. A high-speed motion picture camera viewed the interior through a window port in the bottom of the flame chamber.

Seven test firings were made in the subscale flame chamber using gasoline/air mixtures at an injection equivalence ratio ranging from 1.1 to 1.3 (A/F = 13.29 to 11.24). The injection velocity was 1.52 m/s (5 ft/s) through the 15.2-cm- (6-in.-) diameter piping. Three tests were made with a dual 20-mesh screen arrester installed in the Pres-Vac housing, and four were made with the arrester screens removed. Energetic flames were recorded in the chamber when ignition was made after the hydrocarbon analyser measured an equivalence ratio of 0.7 (A/F = 20.88) or higher in the exhaust flow. The flames entered the piping on every test where the screen arrester was removed. On the first two tests with the screen arrester installed, the flames were quenched. However, on the last test the flame did penetrate the dual 20-mesh screen arrester and enter the facility piping. The motion picture data from this test showed that the hydrogen/air spark igniter was still burning at the time the propagating flame entered the arrester housing. This would have resulted in excessive flame speed that caused the arrester failure. Posttest inspection revealed no damage to the screen arrester.

Both chamber diaphragms ruptured and burned on all tests. The peak chamber pressure rise recorded ranged from 2.07 to 2.76 kN/m$^2$ (0.3 to 0.4 psid). The visible flame plume emitted from both ends of the chamber extended for a distance of about 1 m (3.3 ft.). All instrumentation and cabling within this area required flame protective covering. The audible noise associated with diaphragm rupture was minimal. Flashback flame in the facility piping did not produce detonations.

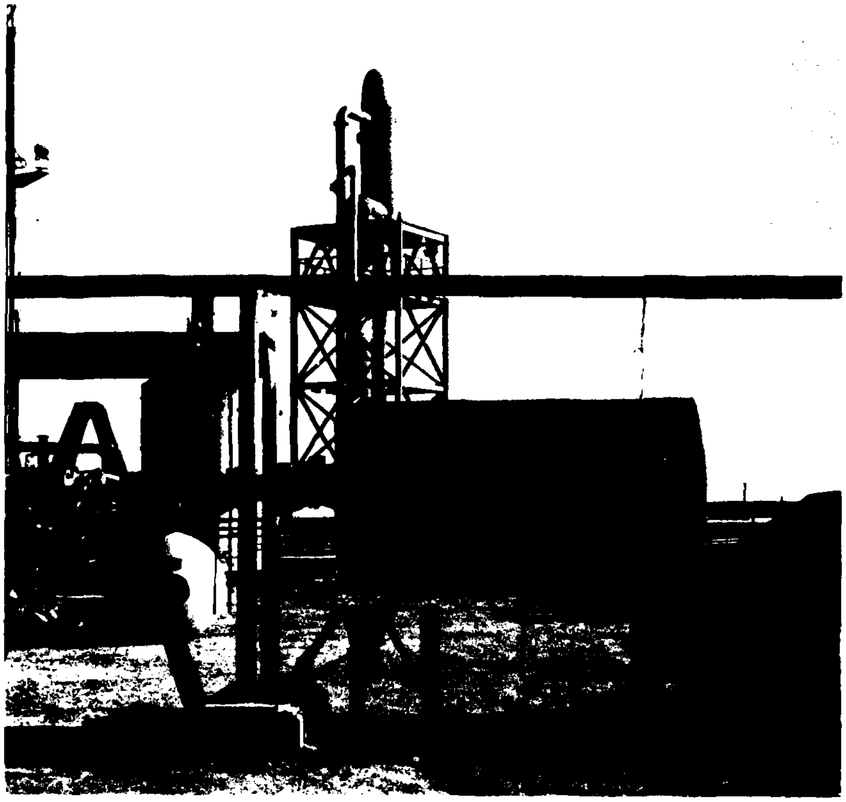


Figure 6-1. [illegible] Flame Test Chamber Installation on B-Stand

[illegible]

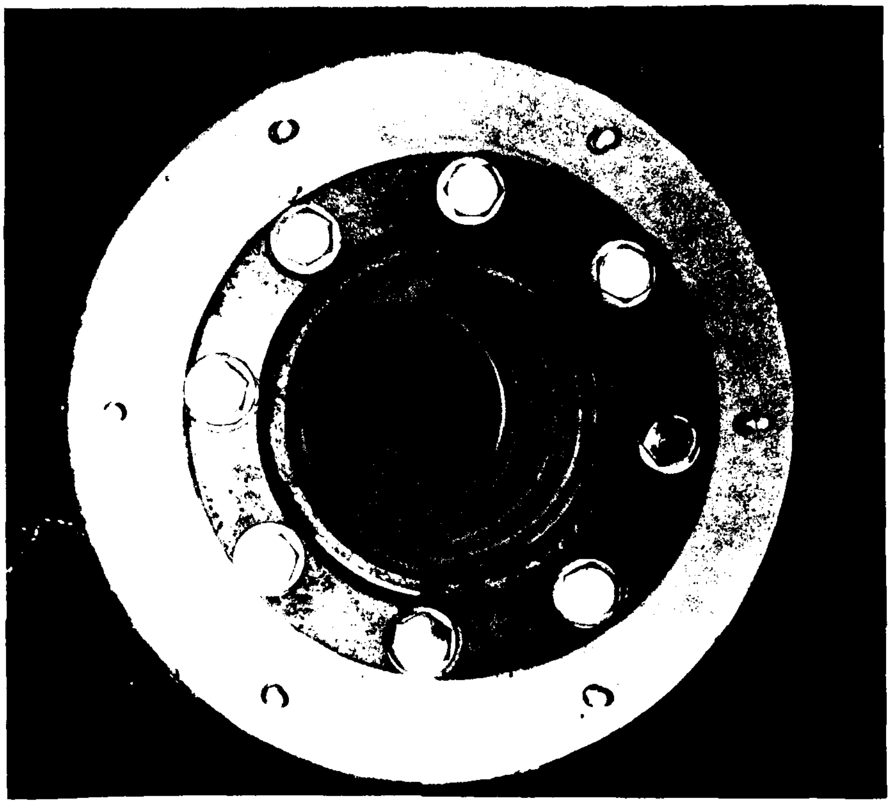
[illegible] described in Subsection III-[illegible] and shown in Figure [illegible]. [illegible] commercial-grade propane for [illegible] propane air mixture [illegible] = [illegible]. A total of twenty-[illegible] different test configurations [illegible], [illegible] test firings were made [illegible] arrester [illegible]. Ignition and combustion [illegible] analyser indicated [illegible] = [illegible]. With the igniter in the [illegible], [illegible] the test arrester. [illegible] the initial [illegible], [illegible] light entering the [illegible]. [illegible] not be calculated [illegible].

The igniter was relocated to the center of the chamber and the test firings were repeated. With this configuration, the flame sensors recorded flame propagation in both the upstream and downstream directions before the chamber diaphragms were blown out. Calculated flame speeds ranged from 1.5 to 4.6 m/s (5 to 15 ft/s) and the flame did not penetrate the screen arrester. All chamber pressure sensors simultaneously recorded a peak pressure rise around 1000 $N/m^2$ (0.145 psid) just before the diaphragms ruptured.

The igniter was relocated to the upstream position, which placed the point source of ignition only 76.2 cm (30 in.) from the downstream face of the screen. One test firing was made with this configuration where the flame penetrated through the screen arrester and into the facility piping. Posttest inspection did not reveal any damage to the screens. Motion pictures taken of this test showed the ignition sequence and the rapidly expanding spherical flame front. It was estimated that the flame speed was in excess of 15.2 m/s (50 ft/s). This unusually high flame speed was most likely caused by the localized influence of the hydrogen/air spark igniter that was programmed for 2.0 seconds duration. The igniter duration was reprogrammed to only 0.2 seconds (200 ms) on all subsequent tests; this eliminated the high initiation flame speed.

When the igniter was relocated to the downstream position, a 1.52-m- (5-ft.-) diameter aluminum plate was installed to cover the central area of the plastic diaphragm on the flame chamber exit. This flame shield covered about 40% of the total exposed area and delayed the rupture of the diaphragm for a sufficient length of time to allow the flame to traverse the length of the chamber. Motion pictures taken of test firings after this modification showed that the flame propagation path was predominantly in the lower half of the chamber. It is believed that this is caused by gravitational stratification of the fuel/air mixture as it enters the chamber. The 1.52-m/s (5-ft/s) injection velocity is not sufficient to produce turbulent mixing within the large chamber volume. It is, however, representative of the worst-case condition of a fuel storage tank venting vapors on a calm day. The results would be a flammable concentration of fuel vapors collecting in the tank area, causing a very hazardous condition. In the test chamber, the stratified flame produced very inconsistent readings on the flame sensors mounted along the horizontal center line. To correct this situation, the flame sensors were relocated along the top center line, where the field of view looking down into the chamber included the low level flames. The resulting flame speed measurements were much more consistent.

The flame screen assembly, which is mounted in the center of the Pres-Vac housing, was 20.3 cm (8 in.) upstream of the exit flange. In this position, the screen surface was not visible to the motion picture camera and the flashback flame impingement on the surface of the screen could not be photographed. For the last series of checkout tests, the Pres-Vac housing was replaced with a short 15.2-cm- (6-in.-) diameter flanged pipe spool section to provide the adaptor mounting for the screen flame arresters. The screens were installed between two flanges at the pipe spool exit, where they would be in full view of the motion picture camera. Figure 6-2 is a photograph of a single 30-mesh screen arrester mounted in the pipe spool adapter. Two test firings were made with this test assembly using propane and air mixture at an equivalence ratio of 1.1 and a flow velocity of 1.52 m/s (5 ft/s). Both the upstream and downstream igniter positions were used. Flame speeds from 4.5 to 7.62 m/s (15 to 25 ft/s) were recorded and the flame did not penetrate the single 30-mesh screen arrester on either test.



started to evaluate the four selected types of flame arresters with one or more of the eight preselected fuels. To reduce the number of possible tests, a standard test condition was established that would use an injection equivalence ratio (1.0 to 1.2) producing the theoretical maximum flame speed for the particular fuel/air mixture in use and an inlet piping flow velocity of 1.52 m/s (5 ft/s). Ignition would be initiated at an equivalence ratio (0.7 to 0.9) well above the lower flammability limit as measured by the total hydrocarbon analyser sampling the mixture flowing in the exhaust-burn stack.

SECTION VII

DESCRIPTION OF FLAME ARRESTER TEST ASSEMBLIES

A. GENERAL

The U.S. Coast Guard has approved the use of both a single 30-mesh screen and the dual 20-mesh screen configuration for screen flame arresters on U.S. flag vessels. Their purpose is the prevention of flame passage from the open deck into cargo tanks through vent outlets, ullage ports, hatches, or butterworth plates. The wire cloth material used for these screens must be resistant to the marine environment, i.e., resistant to chemical corrosion and salt water rusting. In addition, the wire material must be resistant to high-temperature oxidation in the event an accidental flame impinges on the screen surface for a prolonged period of time.

These requirements served as guidelines for the selection of flame screen arresters to be experimentally evaluated as part of the U.S. Coast Guard funded portion of this program. The NASA funded portion was directed at evaluating two generically different types of flame arresters, namely the spiral-wound, crimped metal ribbon, and the packed bed of Ballast rings. These two types of flame arresters have been shown to be very effective in quenching gasoline/air mixture detonations in a piping system, as reported in Reference 2-10. The propagating flame speeds for detonations were in excess of 1800 m/s (5906 ft/s). It remained to be demonstrated that these arresters are also effective against flames with speeds in the range of 1.5 to 9.1 m/s (5 to 30 ft/s), and that they remain effective under sustained burning test conditions for periods up to 30 minutes.

B. SINGLE 30-MESH SCREEN ARRESTER

The single 30-mesh screen arrester was made from standard-grade stainless-steel type 316 wire cloth having the following dimensions:

| | |
|---|---|
| Mesh size: | 30 × 30 per lineal inch |
| Wire diameter: | 0.033 cm (0.013 in.) |
| Hydraulic radius: | 0.0516 cm (0.0203 in.) |
| Open area: | 37.1% |

The type 316 stainless-steel wire is highly resistant to chemical corrosion and rusting. It will also resist thermal oxidation at temperatures up to 760°C (1400°F). Nichrome wire has a higher thermal oxidation resistance, up to 972°C (1700°F), but is less readily available in wire cloth weaves.

The single screen, with a Vellumoid gasket on either side, was installed between the exit flange of the 15.2-cm- (6-in.-) diameter pipe spool adapter and a bolted-up, slip-on flange used for clamping, as shown in Figure 6-2. The fuel/air mixture flow velocity in the facility piping varies inversely with the cross-sectional flow area, therefore the standard 1.52-m/s (5-ft/s) flow velocity increases to 4.1 m/s (13.5 ft/s) in passing through the 30-mesh screen attached at the end of the pipe.

## 7.[illegible] DUAL 20-MESH SCREEN ARRESTER

The dual 20-mesh screen arrester was made from standard grade stainless-steel type [illegible] wire cloth having the following dimensions:

| | |
|---|---|
| Mesh size: | 20 × 20 per lineal inch |
| Wire diameter: | 0.041 cm (0.016 in.) |
| Hydraulic radius: | 0.086 cm (0.034 in.) |
| Open area: | 46.2% |

The two screens were installed on the pipe spool adapter using the same method as the single screen, but with the addition of a 2.54-cm- (1.0-in.-) thick spacer separating the two screens. An exploded view of the components in this assembly is shown in Figure 7-1, and the test installation is shown in Figure 7-2. The [illegible] air mixture flowing at standard conditions in the facility piping accelerated to [illegible] m/s ([illegible] ft/s) during passage through the 15.2-cm- (6-in.-) diameter 20-mesh screens.

## 7.[illegible] SPIRAL-WOUND, CRIMPED METAL RIBBON ARRESTER

The spiral-wound, crimped metal ribbon arrester was the optimum configuration [illegible] as the results of the parametric phase of the testing reported in Reference [illegible]. It was made from a commercially available Shand and Jurs spiral-wound, crimped stainless-steel core element having the following dimensions:

| | |
|---|---|
| Diameter: | 30.5 cm (12 in.) |
| Length (L): | 20.3 cm (8 in.) |
| Ribbon thickness: | 0.0089 cm (0.0035 in.) |
| Crimp height: | 0.160 cm (0.063 in.) |
| Crimp width: | 0.350 cm (0.138 in.) |

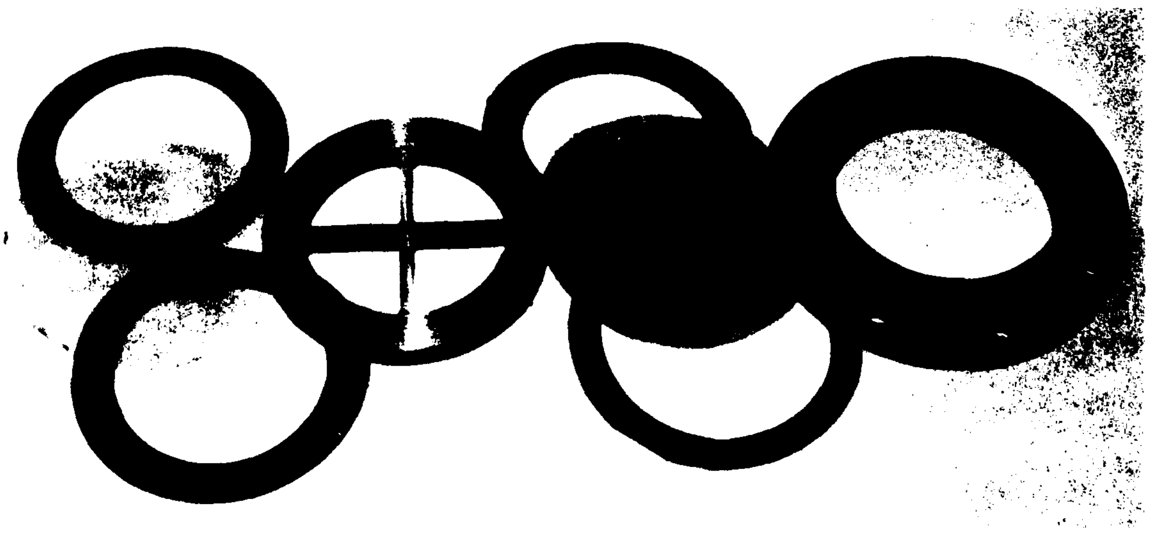
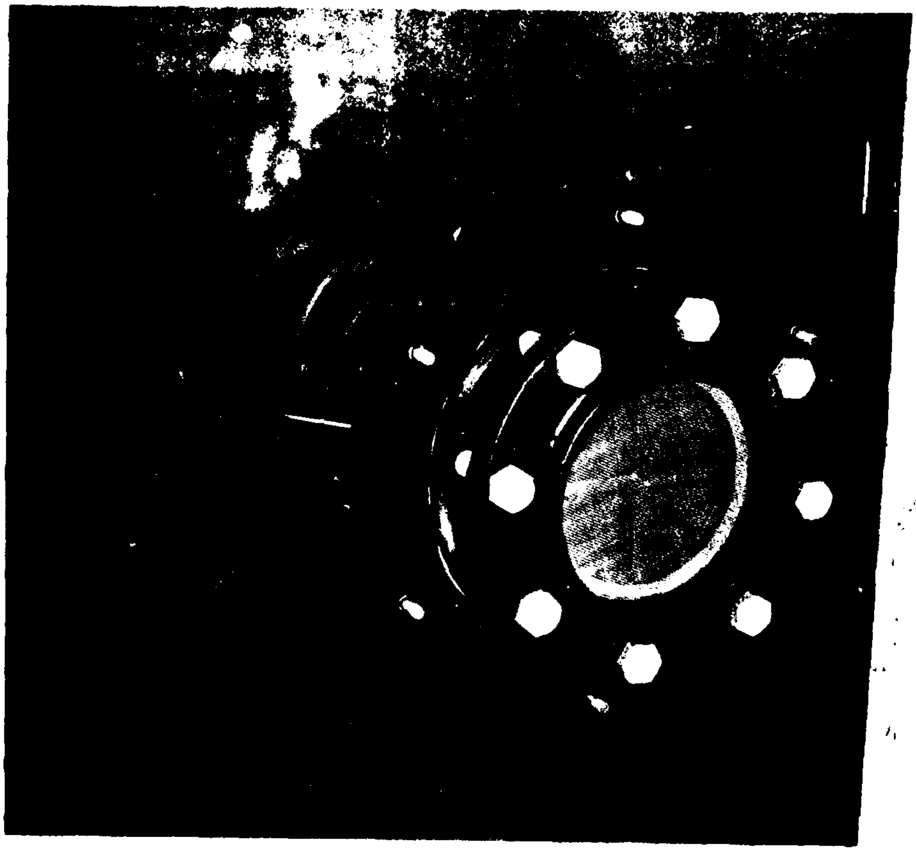
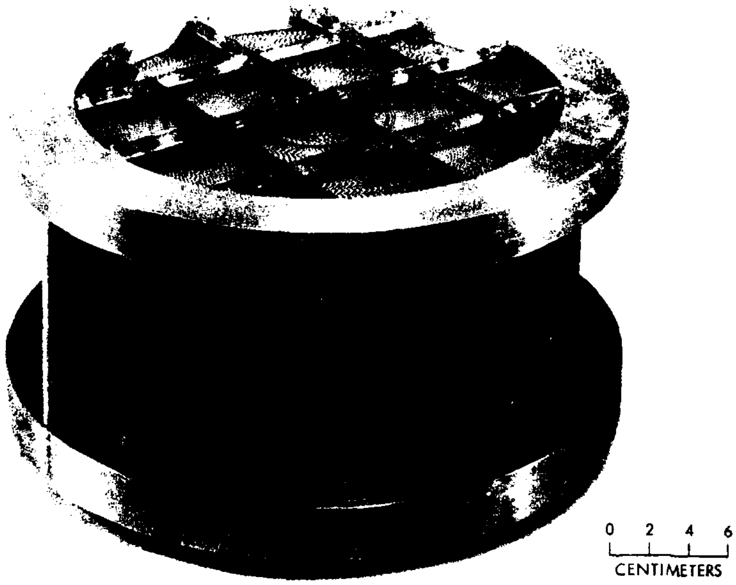
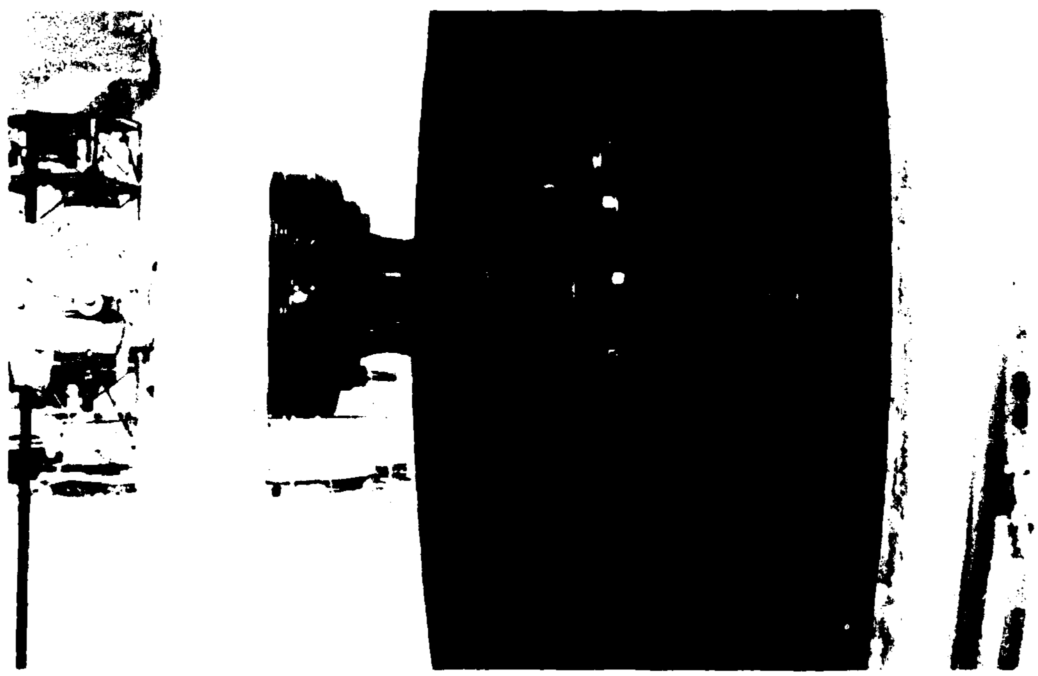


Figure 7-1. Exploded View of Components for a Dual 20-Mesh Screen Arrester





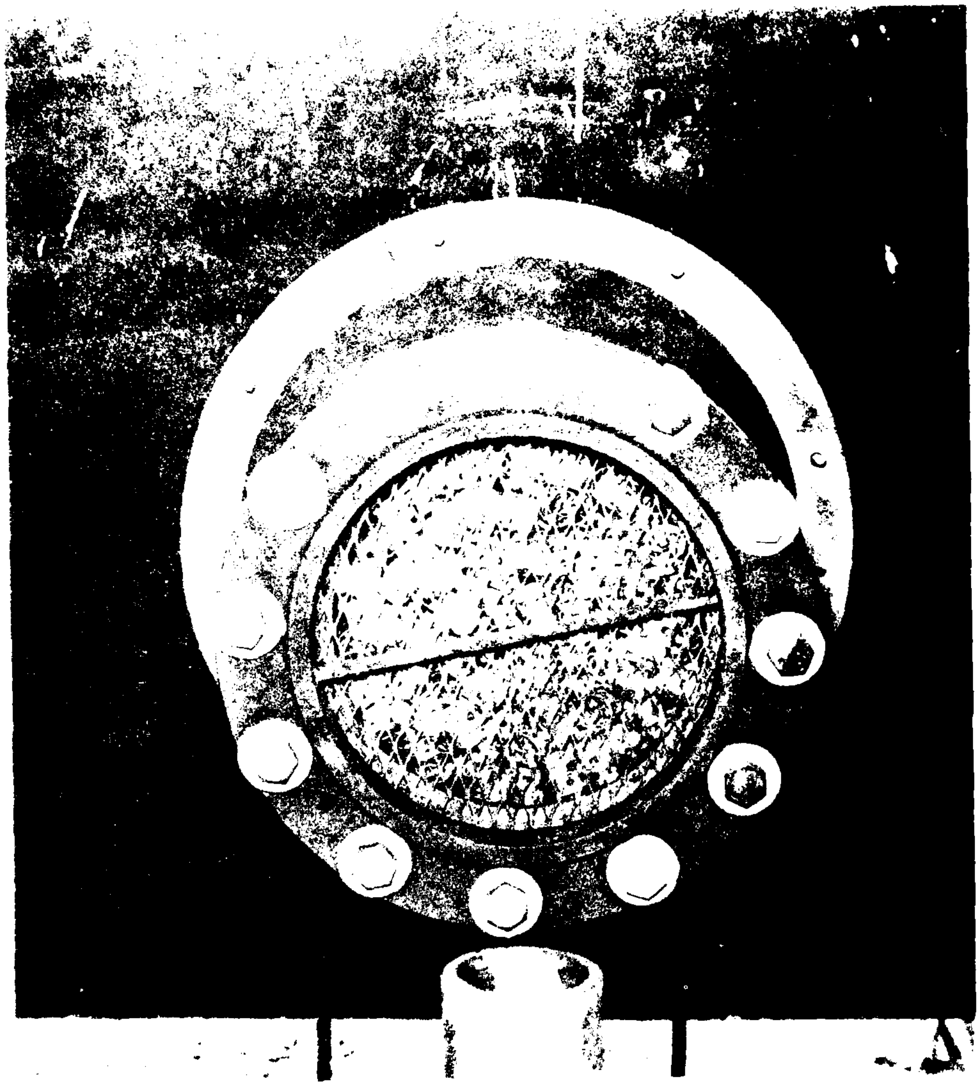
[illegible] installation

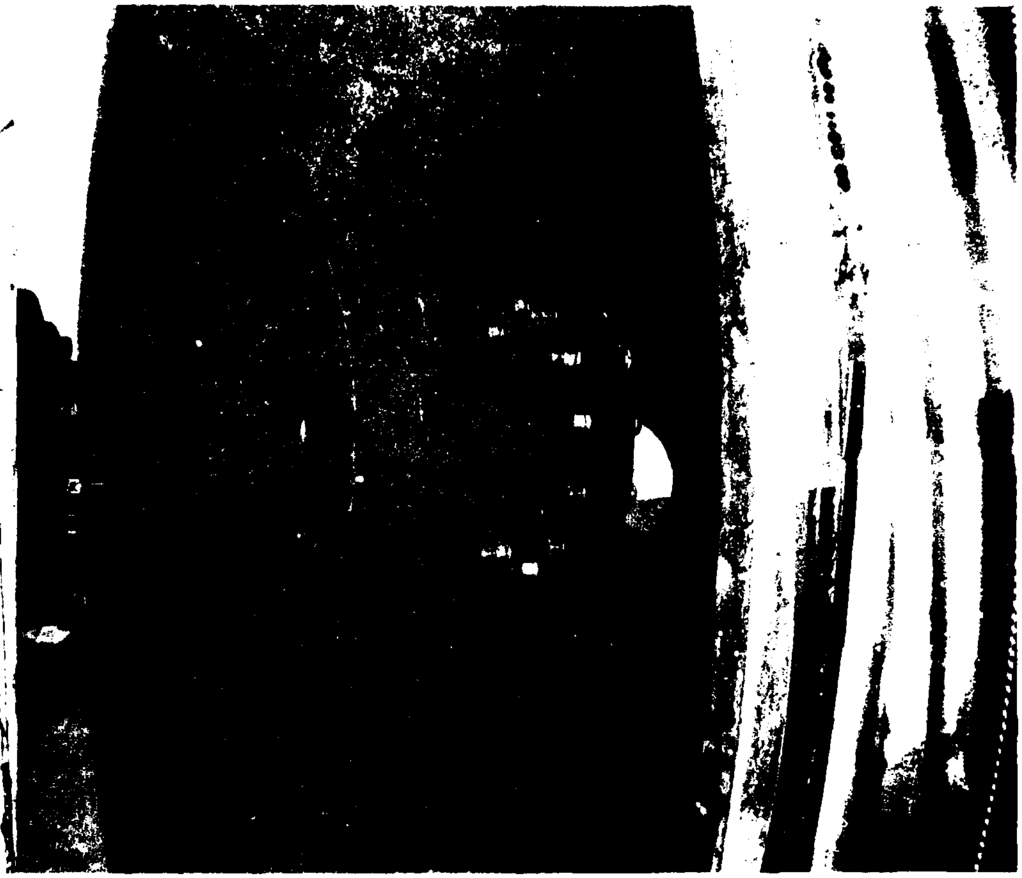
E. PACKED BED OF BALLAST RINGS ARRESTER

The configuration for the packed bed of Ballast rings arrester was also developed during the parametric phase of testing reported in Reference 2-16. It has the following optimized dimensions:

| | |
|---|---|
| Bed diameter: | 25.4 cm (10 in.) |
| Bed length: | 45.7 cm (18 in.) |
| Bed volume: | 3605 cc (1419 cu. in.) |
| Packing material: | aluminum Ballast rings |
| Ring size: | 2.54 cm (1.0 in.) in diameter × 2.54 cm (1.0 in.) long |
| Open area: | 60% (estimated) |

The rings were randomly packed in 25.4-cm- (10-in.-) diameter flanged pipe housing and held in place with an expanded metal grid, as shown in Figure 7-5. A flanged concentric pipe reducer, 25.4-cm to 15.2-cm (10-in. to 6-in.) diameter, adapted the inlet end of the arrester housing for installation on the exit of the facility piping as shown in Figure 7-6. The estimated fuel/air mixture flow velocity through this arrester at the standard test condition was around 0.9 m/s (3.0 ft/s).





# SECTION VIII

# FLASHBACK FLAME ARRESTER TESTS

## A. TEST PROGRAM PLAN

The test program for screen flame arresters followed the logic diagram presented in Figure 8-1. After the selection of the flame arrester test configurations, the first screening test series was performed in the flashback flame chamber to evaluate both the single 40-mesh and the [illegible]-mesh screen arresters with a propane/air mixture. Propane was selected as the first test fuel because it has one of the lowest probable flame speeds of the representative bulk cargo fuels. The upstream igniter position was used first; it was thought to produce the less severe flame speed condition because of the shorter run-up distance for flame propagation. This was followed by tests using the downstream igniter position, assuming that it was more severe. A minimum of three test firings were made for each test configuration to determine the success or failure of the arrester. If a screen flame arrester failed to quench the flashback flame in any of these initial tests, it was to be deleted from the program.

The second screening test series was performed to evaluate the successful flame arrester configuration(s) from the first series, using an ethylene/air mixture because it had the highest probable flame speed of the representative bulk cargo fuels. Both the upstream and downstream igniter positions were used. Upon completion of the ethylene/air mixture tests, one or both of the screen flame arresters was to be selected for additional testing with the six alternate types of fuel/air mixtures. The selection of arrester configurations was made by the U.S. Coast Guard, based upon the test results and the recommendations provided by [illegible].

Additional evaluation test series were made in the flame chamber with the selected arrester configurations using the following representative bulk cargo fuels: (1) acetaldehyde, (2) butane, (3) ethyl ether, (4) gasoline, (5) methyl alcohol, and (6) toluene. The igniter position was selected to produce the most severe flashback flame propagation condition as determined from the measured flame speed advancing toward the face of the test arrester in the first two screening test series.

A final evaluation test series was made using the successful arrester configurations from the previous testing to evaluate their heat-up and quenching capabilities in the sustained flame facility. The flame from a propane/air mixture at the standard test condition was stabilized on the downstream face of the arrester for a period of [illegible]0 minutes. These tests were used to determine if the arrester can continue to function after reaching an elevated steady-state, flash-back temperature without structural damage. A single test for the full duration of [illegible] minutes, without a flame penetration, was sufficient to demonstrate the successful performance of any arrester configuration. If a flame did penetrate the test arrester, the test would be repeated to verify the failure.

The two [illegible]-funded flame arrester configurations, the spiral-wound, crimped [illegible] and the packed bed of aluminum [illegible] rings, were inserted into the program [illegible] with the second screening test series. They were evaluated in the

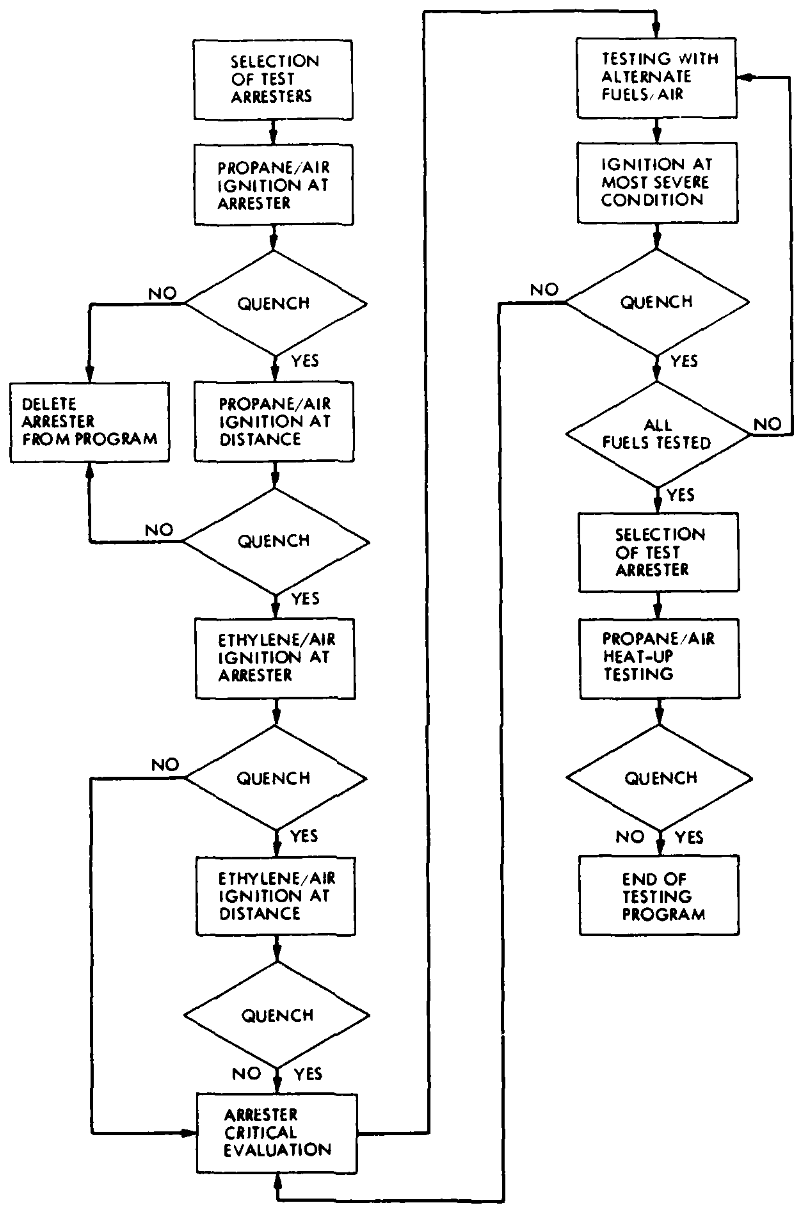



Figure 8-1. Screen-Type Flashback Flame Arrester Test Program Logic Diagram

flashback flame chamber with three fuels: (1) propane, (2) ethylene, and (3) gasoline. The igniter position was selected for the most severe test condition. They were also evaluated in the sustained burning facility using both propane/air mixture and ethylene/air mixture at the standard test condition.

## B. PROPANE/AIR MIXTURE SCREENING TESTS

The first series of screening tests were made with propane air mixture at the standard test condition where the injection equivalence ratio was 1.14 (A/F = 13.75). Fill time required to obtain a good combustible mixture in the flame chamber was 600 seconds. The nominal equivalence ratio at ignition was 0.87 (A/F = 18.02) as measured by the total hydrocarbon analyser sampling the fuel/air mixture in the exhaust-burn stack. Tests were made with the dual 30-mesh screen arrester and the single 30-mesh screen arrester using both the upstream and downstream igniter positions (Test Configuration Nos. 113 to 116). Successful ignition and combustion was achieved on all test firings. The flashback flames did not penetrate either of these screen-type arresters on any test.

The upstream igniter position produced an average flame speed between the point source of ignition and the arrester (F81-F82, Table 4-1) that measured 4.8 m/s (15.7 ft/s). The flame speed moving in the direction of flow (downstream) increased to an average of 13.6 m/s (44.6 ft/s) before it exited the downstream end of the flame chamber (F86-F87). Average peak pressure rise in the chamber (F81 to F87) ranged from 1139 to 974 N/m$^2$ (0.165 to 0.141 psid). A plot of the results from these tests is shown in Figure 8-2. Also shown on this plot are the flame speeds in the facility piping that occurred on the last checkout test, when an arrester was not installed. The flame entered the piping (F81-F73) at 2.3 m/s (7.5 ft/s) and accelerated up to 18.9 m/s (62.0 ft/s) at the facility inlet arrester (F21-F12). A tabular summary of averaged flame speed data and peak pressure rise data is presented in Table 1-1. A tabular summary of all steady-state data is presented in Appendix B and a tabular summary of all transient-state data is presented in Appendices C and D.

The average flame speeds recorded in this test chamber when using the downstream igniter position (Test Configuration Nos. 114 and 115) were more uniform and lower in value, as shown in the data plot, Figure 8-3. A maximum flame speed of 4.2 m/s (13.8 ft/s) occurred just upstream of the igniter (F86-F87). The flashback flame speed propagating against the direction of flow (upstream) was only 3.0 m/s (9.8 ft/s). This is about one half the speed obtained using the upstream igniter position. Peak pressure rise data were also more uniform and slightly lower, with an averaged value of 810 N/m$^2$ (0.117 psid).

The results of these first screening tests indicate that both the dual 30-mesh screen arrester and the single 30-mesh screen arrester are effective in quenching flashback flames with a nominal flame speed up to 6.3 m/s (20.7 ft/s). The more severe test condition in the flame chamber is produced when the igniter is located in the upstream position. The flame speed data obtained from the motion picture films corroborate these test results. It was apparent in the films that the degree of intensity (brightness) in the propagating flame front correlated to the regions of optimum fuel/air mixture ratio and higher levels of localized turbulence. When the upstream igniter position was used, a bright band

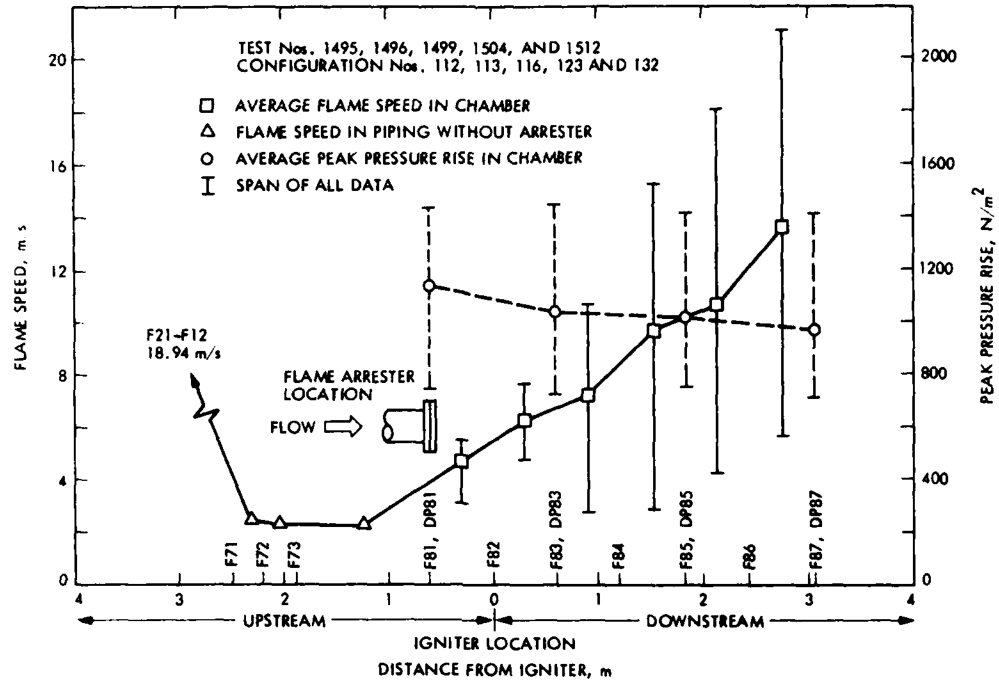



Figure 8-2. Propane/Air Mixture Using Upstream Igniter Position Test Results

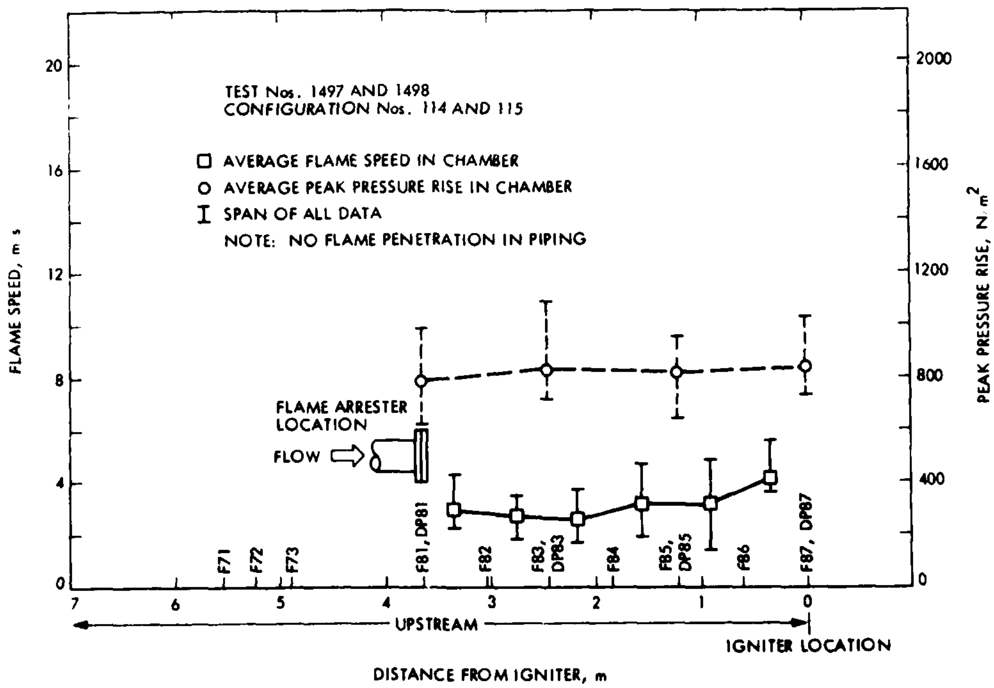



Figure 8-3. Propane/Air Mixture Using Downstream Igniter Position Test Results

of flame could be seen accelerating upstream through the center core flow of the plume of the fuel/air mixture as it expanded from the facility piping. The fuel/air mixture ratio in the expanding plume became stratified by gravitational effects: the heavier hydrocarbon vapors settled to the bottom of the test chamber. When the downstream igniter position was used, the propagating flame could be seen in the films concentrated mainly in the lower half of the chamber with a very broad and diffused flame front moving relatively slowly upstream. This flame front increased in brightness and accelerated in speed as it progressed up the plume to the test arrester installed on the facility piping.

### [illegible]. ETHYLENE/AIR MIXTURE SCREENING TESTS

The second series of screening tests were made with an ethylene/air mixture at the standard test conditions. The injection equivalence ratio was 1.15 (A/F = 12.86) for maximum flame speed. Fill time required to charge the flame chamber with a combustible mixture of this gaseous fuel was reduced to 400 seconds. The nominal equivalence at the time of ignition was 0.70 (A/F = 21.1). Both the dual 20-mesh screen arrester and the single 30-mesh arrester were used in these tests with upstream and downstream igniter positions (Test Configuration Nos. 117 to 124).

A problem started on the first test when it was discovered that a sustained flame developed inside the exhaust-burn stack piping during the chamber filling operations. It is believed the flame originated from the natural gas fired burner at the top of the stack. Once the ethylene/air exhaust reached a flammable mixture level, a flashback flame from the burner impinged on the exit arrester. The relatively high flame speed of the ethylene/air mixture and the low flow velocity at this location allowed the flame to penetrate into the core of the arrester. It heated the stainless-steel crimped ribbon up to the spontaneous ignition temperature (490°C) for ethylene fuel. At this point, the flame passed through the exit arrester, propagated up the piping, and held on the downstream face of the inlet arrester. Other than blistering the paint on the outside of the piping, this caused no structural damage.

In the inlet arrester of the exhaust-burn stack had a core element made of spiral-wound, crimped aluminum ribbon. It was four times as long as the exit arrester, 15.2 cm (6 in.) compared to 3.8 cm (1.5 in.), and approximately the same diameter. This larger mass of metal, having higher heat capacity, apparently prevented the lean ethylene/air flame from penetrating through the inlet arrester. Consequently, the exit arrester was replaced with a unit similar to the inlet arrester. The results indicated no further incidents of sustained flames in the exhaust-stack piping and the test program to evaluate screen-type arresters using ethylene/air mixture flames continued.

The average flame speeds recorded in the flame chamber when using the downstream igniter position (Test Configurations No. 119 and 121) ranged from 7.8 m/s (25.6 ft/s) at the igniter (F86-F87) to 4.4 m/s (14.4 ft/s) at the arrester (F81-F82). The average peak pressure rise in the chamber was 931 $N/m^2$ (0.135 psid). A plot of the test results are shown in Figure 8-4. Both types of screen flame arresters were successful in quenching these ethylene/air mixture flashback flames.

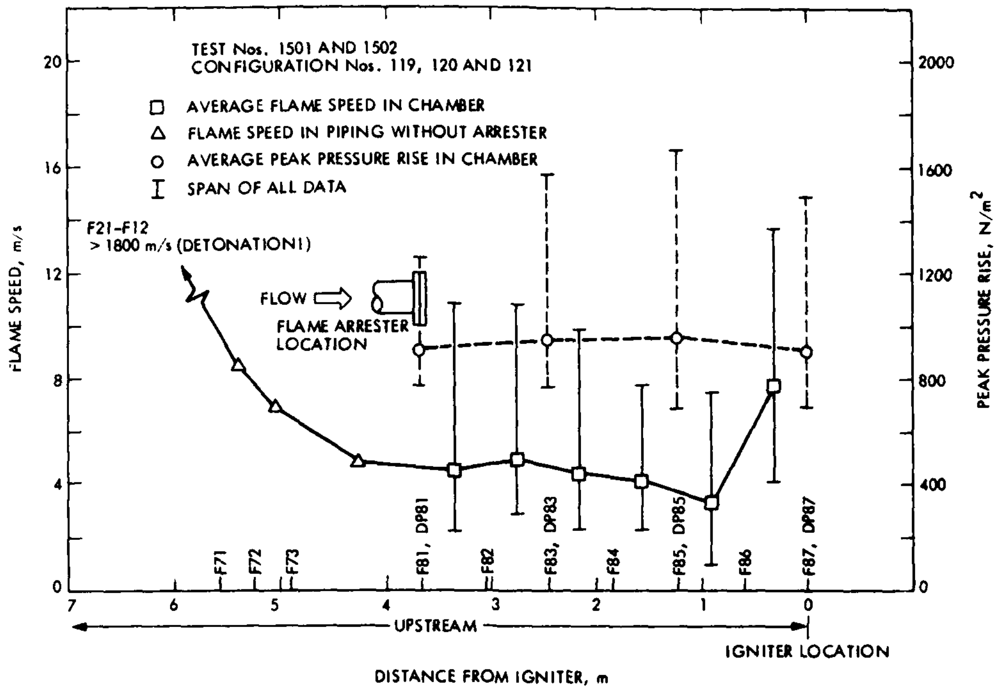



Figure 8-4. Ethylene/Air Mixture Using Downstream Igniter Position Test Results

When the arrester was removed from the end of the facility pipe, the flame entered the pipe (F81-F73) at a speed of 4.9 m/s (16.1 ft/s) and accelerated to a detonation at the inlet arrester (F21-F12) with speeds in excess of 1800 m/s (5905 ft/s). The detonation did not produce any damage to the test facility systems.

The average flame speeds recorded in the flame chamber when using the upstream igniter position (Test Configuration Nos. 117, 118, and 122) ranged from 6.6 m/s (21.6 ft/s) at the arrester (F81-F82) to 16.3 m/s (53.5 ft/s) at the downstream chamber exit (F86-F87). The average peak pressure rise in the chamber was 1102 $N/m^2$ (0.160 psid). A plot of the test results are shown in Figure 8-5. The single 30-mesh screen arrester was successful in quenching all flashback flames, whereas the dual 20-mesh screen arrester failed to quench any of the flashback flames in three test firings. The flame that penetrated through the arrester screen housing decelerated briefly to 3.9 m/s (12.8 ft/s) in the facility piping (F81-F73), and then quickly accelerated to a detonation before reaching the facility inlet arrester (F21-F12). Posttest inspection of the screens following each flame penetration did not reveal any damage to the screen wire that could have caused this failure.

The results of the second screening tests indicate that the single 30-mesh screen arrester is effective in quenching flashback flames with nominal flame speeds up to 6.6 m/s (21.6 ft/s). The dual 20-mesh screen arrester is not effective at this higher flame speed, and the limiting flame speed will have to

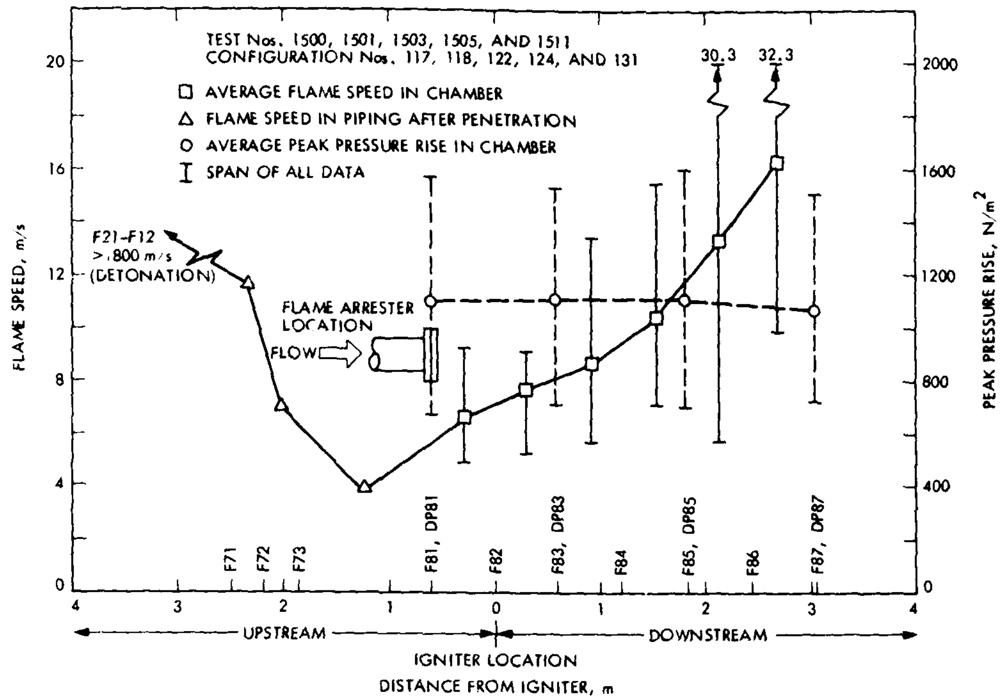



Figure 8-5. Ethylene/Air Mixture Using Upstream Igniter Position Test Results

be determined from additional tests. The upstream igniter position again resulted in the more severe test conditions when using ethylene/air mixture in the flame test chamber. Photographic data of flame speeds taken from the motion picture films corroborated these test results. In accordance with the logic diagram, Figure 8-1, the follow-on alternate fuels tests were limited to using the upstream igniter position only.

## D. GASOLINE/AIR MIXTURE TESTS

The first series of alternate fuels tests were made with a gasoline/air mixture at the standard test condition. The injection equivalence ratio was 1.10 (A/F = 17.29) for maximum flame speed. Time required to fill the test chamber varied depending on the ambient temperature, but averaged around 900 seconds. The nominal equivalence ratio for ignition was 0.70 (A/F = 20.89). Tests were made using the dual 20-mesh screen arrester, the single 30-mesh screen arrester, the spiral-wound, crimped stainless-steel ribbon arrester, and the packed bed of aluminum Ballast rings arrester (Test Configuration Nos. 125 to 130). All tests were made with the igniter in the upstream position.

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 4.22 m/s (13.3 ft/s). The highest average flame speed was measured just downstream of the igniter (F82-F83) at 6.01 m/s

(19.7 ft/s); from there it decelerated to only 2.92 m/s (9.6 ft/s) at the flame chamber exit (F86-F87). Average peak pressure rise in the chamber was around 1018 N/m² (0.148 psid). Without any arrester installed, the flashback flame entered the facility piping at 2.00 m/s (6.6 ft/s) and propagated upstream reaching a speed of 5.44 m/s (17.8 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-6.

The dual 20-mesh screen arrester, the single 30-mesh screen arrester, and the crimped ribbon arrester were all successful in quenching the flashback flames from the gasoline/air mixture. The packed bed arrester, in the original test configuration (No. 129), was unsuccessful in quenching the first three firings. Flame sensor data actually recorded an acceleration in flame speed during passage through the bed of rings, possibly caused by induced turbulence. A single 30-mesh screen was inserted between the downstream face of the bed and the retainer grid as shown in Figure 8-7. This test configuration (No. 130) was retested using the gasoline/air mixture, propane/air mixture, and ethylene/air mixture. It proved to be successful in quenching the flashback flame from all three fuel/air combinations. During the testing with ethylene/air mixtures, there was evidence of slight pressure spiking in the facility piping 25 seconds after ignition and concurrent with the lean blowout of the flame holding on the downstream face of the arrester. Posttest inspection of the arrester revealed no damage to the screen wire, but there was discolorationindicating that the impinging ethylene/air flame had heated the screen above 550°C (1022°F).

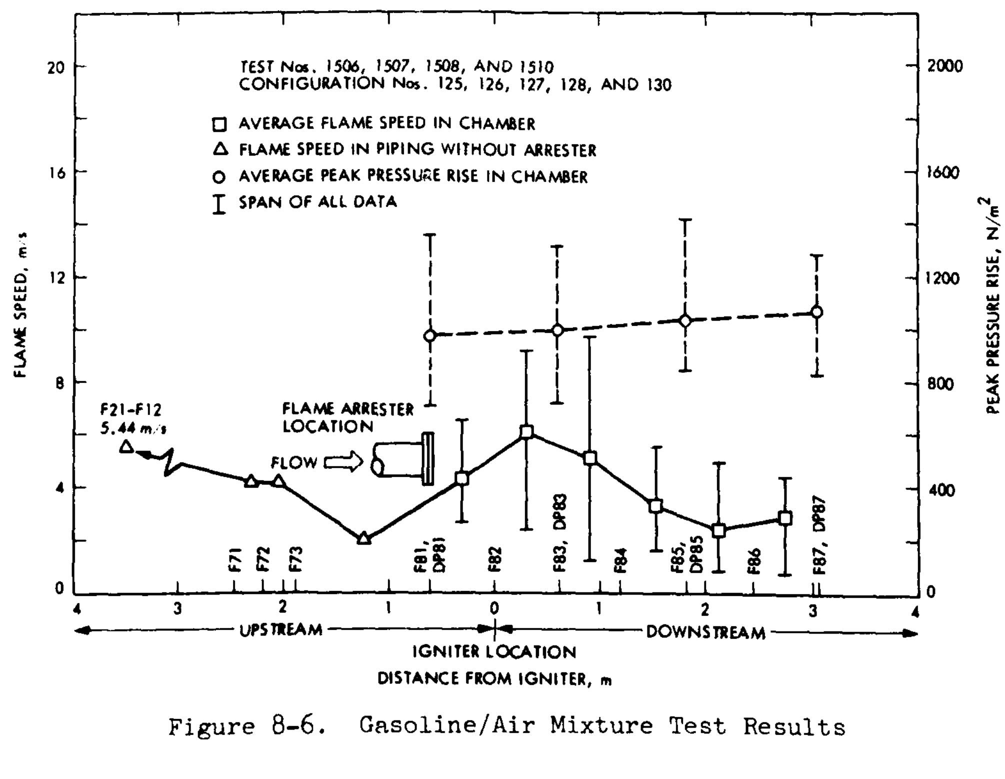
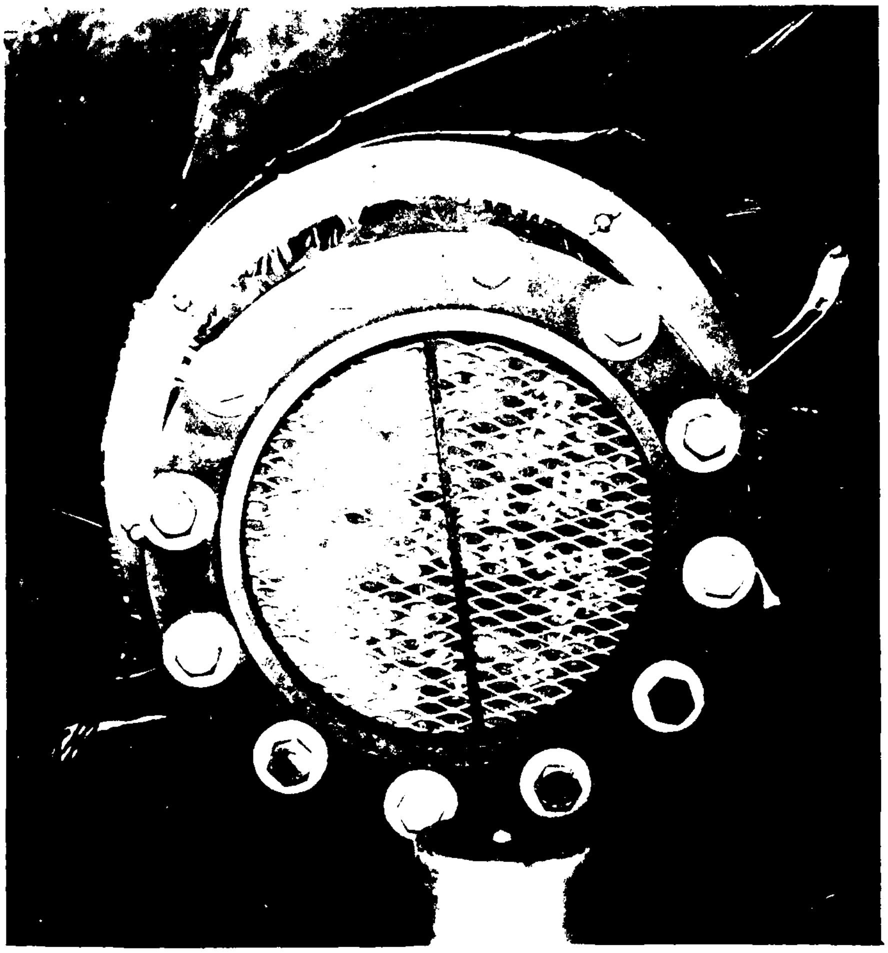



Figure 8-6. Gasoline/Air Mixture Test Results



## E. METHANOL/AIR MIXTURE TESTS

The second series of alternate fuels tests was made with methanol/air mixture at standard test conditions. The injection equivalence ratio was 1.01 (A/F = 6.41) for maximum flame speed. Time required to fill the test chamber averaged 1060 seconds, because of the cold ambient temperatures and the low volatility of methanol. The nominal measured equivalence ratio at ignition was 0.69 (A/F = 9.38). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 133 to 135).

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 4.35 m/s (14.3 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 5.52 m/s (18.1 ft/s). Two flame sensors at the exit of the flame chamber (F86 and F87) were inoperative due to weather conditions. The average peak pressure rise in the chamber was 831 N/m$^2$ (0.120 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of only 2.19 m/s (7.2 ft/s), and was unable to propagate upstream through the facility piping. A plot of the results from these tests is shown in Figure 8-8. Both the dual 20-mesh screens arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the methanol/air mixture.

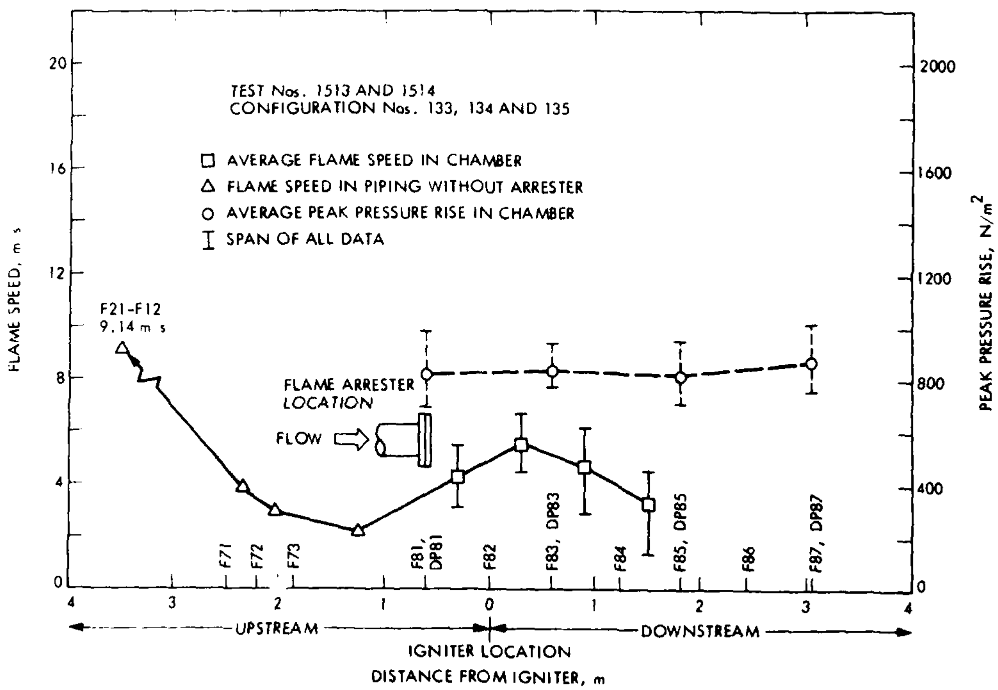



Figure 8-8. Methanol/Air Mixture Test Results

## F. TOLUENE/AIR MIXTURE TESTS

The third series of alternate fuels tests were made with toulene/air mixtures at standard test conditions. The injection equivalence ratio was 1.05 (A/F = 12.86) for maximum flame speed. Time required to fill the test chamber averaged 1070 seconds. The nominal measured equivalence ratio at ignition was 0.68 (A/F = 19.9). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 136 to 138).

The average flame speed between the igniter and the downstream face of the test arresters (F81-F82) was 5.42 m/s (17.8 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 6.27 m/s (20.6 ft/s); from there it decelerated to only 2.65 m/s (8.7 ft/s) at the flame chamber exit (F86-F87). The average peak pressure rise in the chamber was 668 $N/m^2$ (0.098 psid), the lowest value recorded for all fuel/air mixtures. Without a flame arrester installed, the flashback flame entered the facility piping with a flame speed of only 0.61 m/s (2.0 ft/s) and was unable to propagate upstream through the facility piping. A plot of the results from these tests is shown in Figure 8-9. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the toluene/air mixtures.

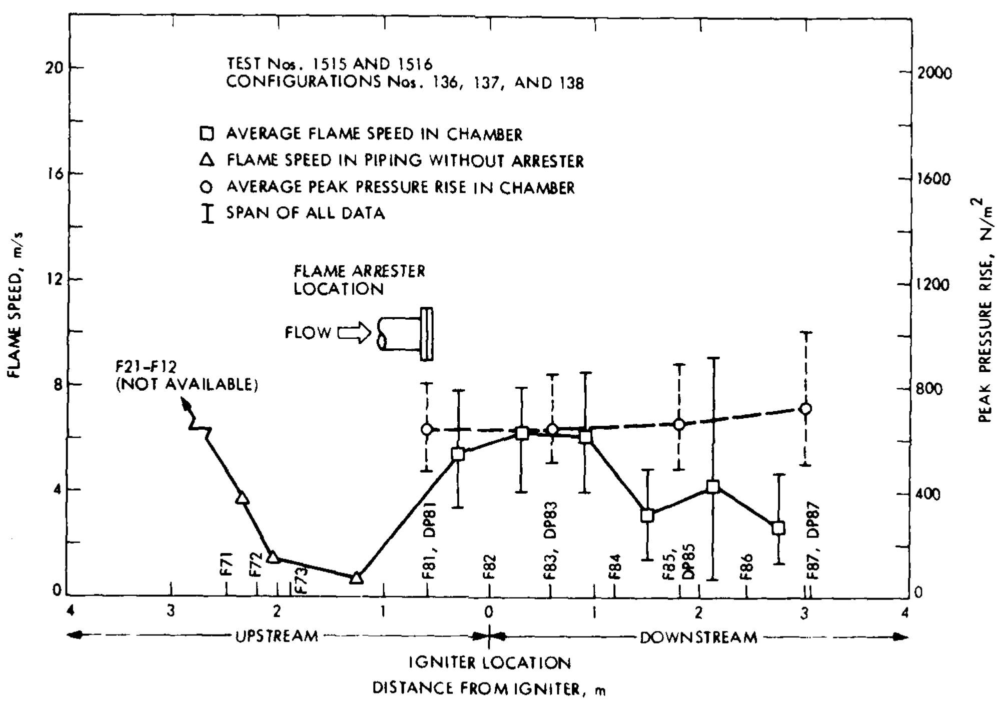



Figure 8-9. Toluene/Air Mixture Test Results

## J. DIETHYL ETHER/AIR MIXTURE TESTS

The fourth series of alternate fuels tests were made with diethyl ether/air mixture at standard test conditions. The injection equivalence ratio was 1.15 (A/F = 9.7[illegible]) for maximum flame speed. Time required to fill the test chamber averaged [illegible]50 seconds. The nominal measured equivalence ratio at the time of ignition was 0.71 (A/F = 15.8). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 139 to 141).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 5.61 m/s (21.4 ft/s). The highest average flame speed measured in the center of the chamber (F84-F85) was 11.95 m/s (39.2 ft/s). These flame speeds were the second highest obtained, next to the ethylene/air mixture. The average peak pressure rise in the chamber was 937 $N/m^2$ (0.136 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 2.98 m/s (9.78 ft/s) and propagated upstream accelerating to 59.43 m/s (195 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-10. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the diethyl ether/air mixture.

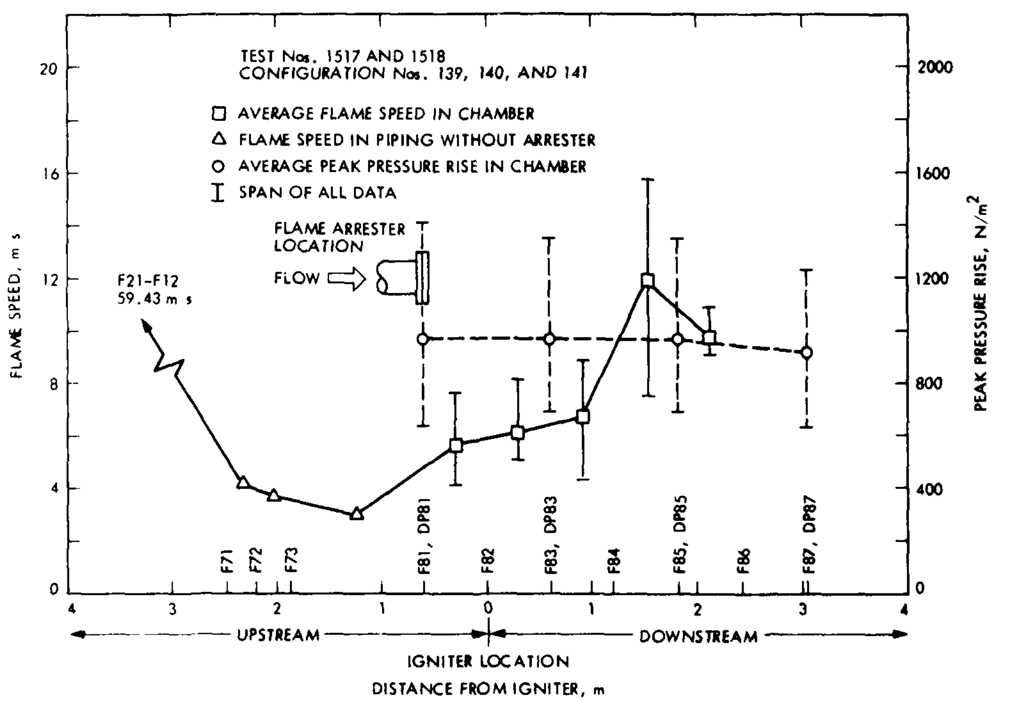



Figure 8-10. Diethyl Ether/Air Mixture Test Results

## H. BUTANE/AIR MIXTURE TESTS

The fifth series of alternate fuels tests were made with butane/air mixture at standard test conditions. The injection equivalence ratio was [illegible] (A/F = 13.68) for maximum flame speed. Time required to fill the test chamber averaged 507 seconds. The nominal measured equivalence ratio at the time of ignition was 0.78 (A/F = 19.8). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 142 to 144).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 3.62 m/s (11.9 ft/s). The highest average flame speed measured just downstream of the igniter (F82-F83) was 5.07 m/s (16.6 ft/s); from there it decelerated to only 2.71 m/s (8.9 ft/s) at the flame chamber exit (F86-F87). The average peak pressure rise in the chamber was 966 N/m² (0.140 psid). Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 2.26 m/s (7.4 ft/s) and propagated upstream accelerating to 17.54 m/s (57.5 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-11. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the butane/air mixtures.

## I. ACETALDEHYDE/AIR MIXTURE TEST

The sixth and final series of alternate fuels tests were made with acetaldehyde/air mixture at standard test conditions. The injection equivalence

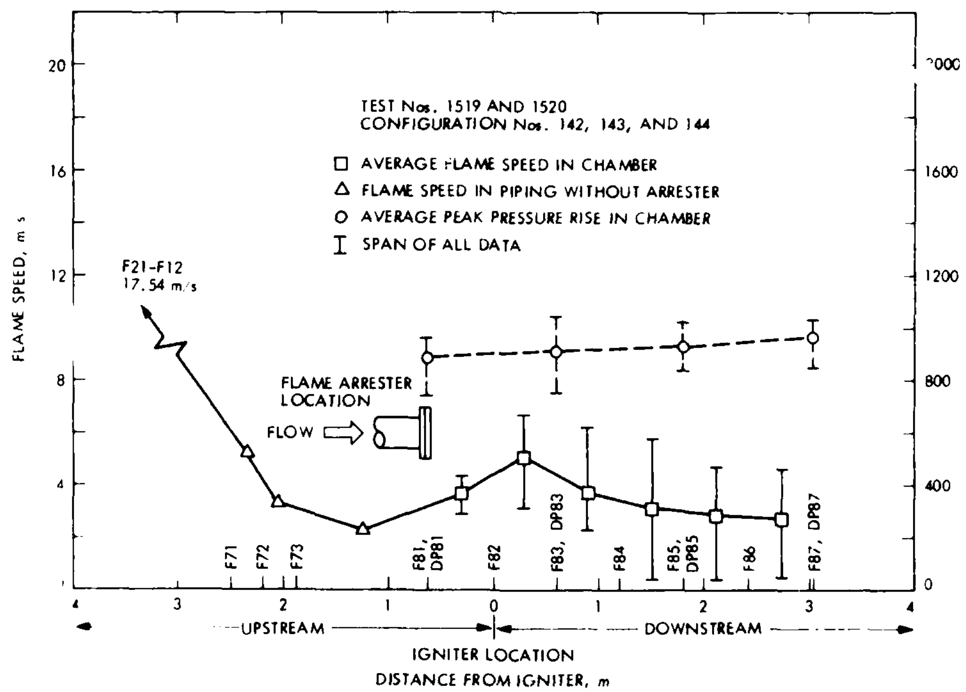



Figure 8-11. Butane/Air Mixture Test Results

ratio was 1.15 (A/F = 6.82) for maximum flame speed. Time required to fill the test chamber averaged 920 seconds. The nominal measured equivalence ratio at the time of ignition was 0.63 (A/F = 12.5). Tests were made with the dual 20-mesh screen arrester and the single 30-mesh screen arrester using the upstream igniter position (Test Configuration Nos. 145 to 147).

The average flame speed between the igniter and the downstream face of the test arrester (F81-F82) was 5.30 m/s (17.4 ft/s). The highest average flame speed measured at the chamber exit (F86-F87) was 12.11 m/s (39.7 ft/s). These flame speeds are about equal to those obtained for the diethyl ether/air mixture. The average peak pressure rise in the chamber was 1102 N/m$^2$ (0.160 psid), which is the same level obtained with ethylene/air mixture. Without an arrester installed, the flashback flame entered the facility piping with a flame speed of 3.22 m/s (10.6 ft/s) and propagated upstream accelerating to 411 m/s (1348 ft/s) at the facility inlet arrester (F21-F12). A plot of the results from these tests is shown in Figure 8-12. Both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful in quenching all flashback flames from the acetaldehyde/air mixture.

J. ARRESTER SELECTION FOR SUSTAINED BURNING TESTS

The tests described above completed the alternate fuel/air mixtures step in the test program logic diagram presented in Figure 8-1. Since both the dual 20-mesh screen arrester and the single 30-mesh screen arrester were successful

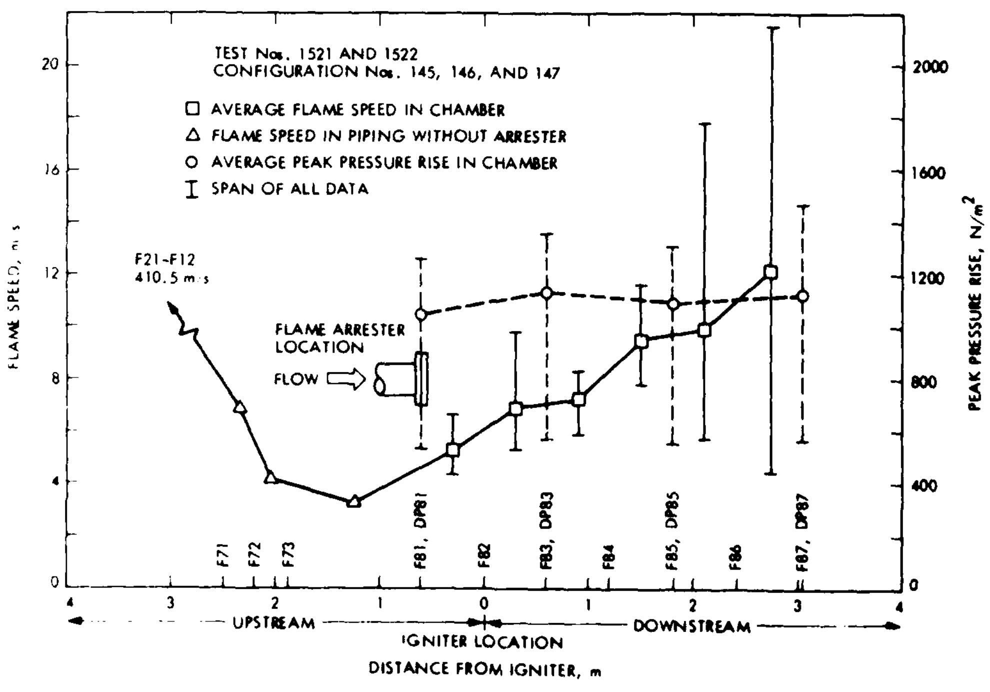



Figure 8-12. Acetaldehyde/Air Mixture Test Results

in quenching all flashback flames from all the alternate fuel tests, they were both designated by the U.S. Coast Guard for sustained burning tests, along with the crimped ribbon arrester and the packed bed arrester for the NASA project.

## SECTION IX

## SUSTAINED BURNING ARRESTER TESTS

### A. PROPANE/AIR MIXTURE TESTS

The first series of sustained burning tests were made with propane/air mixtures at the standard test condition where the injection equivalence ratio was 1.14 (A/F = 13.75). The duration of testing was planned for 30 minutes to allow sufficient time for the test assembly to reach thermal equilibrium. In the event the flame penetrated through the arrester, the test was terminated as quickly as possible to minimize damage to the facility piping and instrumentation.

The dual 20-mesh screen arrester and the single 30-mesh screen arrester were tested in two different test assembly sizes, the original 15.2-cm (6-in.) diameter and a new 25.4-cm (10-in.) diameter. This was done to evaluate the effects of the fuel/air mixture approach velocity and flow-through velocity on the thermal environment at the screens. The spiral-wound, crimped stainless-steel ribbon arrester and the packed bed of Ballast rings arrester were the same configuration that proved successful in the flashback flame testing. All arresters were instrumented with additional thermocouples (Figure 9-1) to measure thermal buildup and to aid in predicting an impending flame penetration when the arrester temperature approached the spontaneous ignition temperature of the fuel/air mixture.

The following results are for the propane/air mixture sustained burning tests. A tabular summary of the test data is presented in Appendix [illegible].

#### 1. Single 30-Mesh Screen Arrester, 15.2-cm Diameter

A schematic drawing of this arrester test assembly (Test Configuration No. [illegible]), presented in Figure 9-[illegible], shows the location of the thermocouple (T7A) used to measure the screen temperature. The small sheath-type thermocouple was mounted with spring loading against the upstream face of the screen. This method was used to maintain point contact and to minimize local flow disturbance. The approaching flow velocity in the 15.2-cm- (6-in.-) diameter pipe adapter housing was [illegible] m/s (5.[illegible] ft/s) and the flow-through velocity in the screen was [illegible]. At the start of testing, the screen temperature reached an initial plateau of [illegible]°C ([illegible]°F) after [illegible] seconds. The temperature continued to increase slowly until it reached [illegible]°C ([illegible]°F) after 30 minutes of operation. The sustained flame from the propane/air mixture did not penetrate through the single 30-mesh screen arrester. A plot of the results is presented in Figure 9-[illegible]. Posttest inspection of the screen revealed no damage or flame erosion and only slight discoloration of the wire mesh.

#### 2. Dual 20-Mesh Screen Arrester, 15.2-cm Diameter

A schematic drawing of this test assembly (Test Configuration No. [illegible]), presented in Figure 9-2, shows the location of the thermocouples (T8A and T8B) used to measure the two screen temperatures. The approaching flow velocity in the 15.2-cm- (6-in.-) diameter pipe was 1.5 m/s (5.0 ft/s) and the flow-through velocity in the screens was 3.3 m/s (10.8 ft/s). Temperature on the downstream screen (T8A) reached an initial plateau of 92°C (198°F) after 120 seconds of operation and

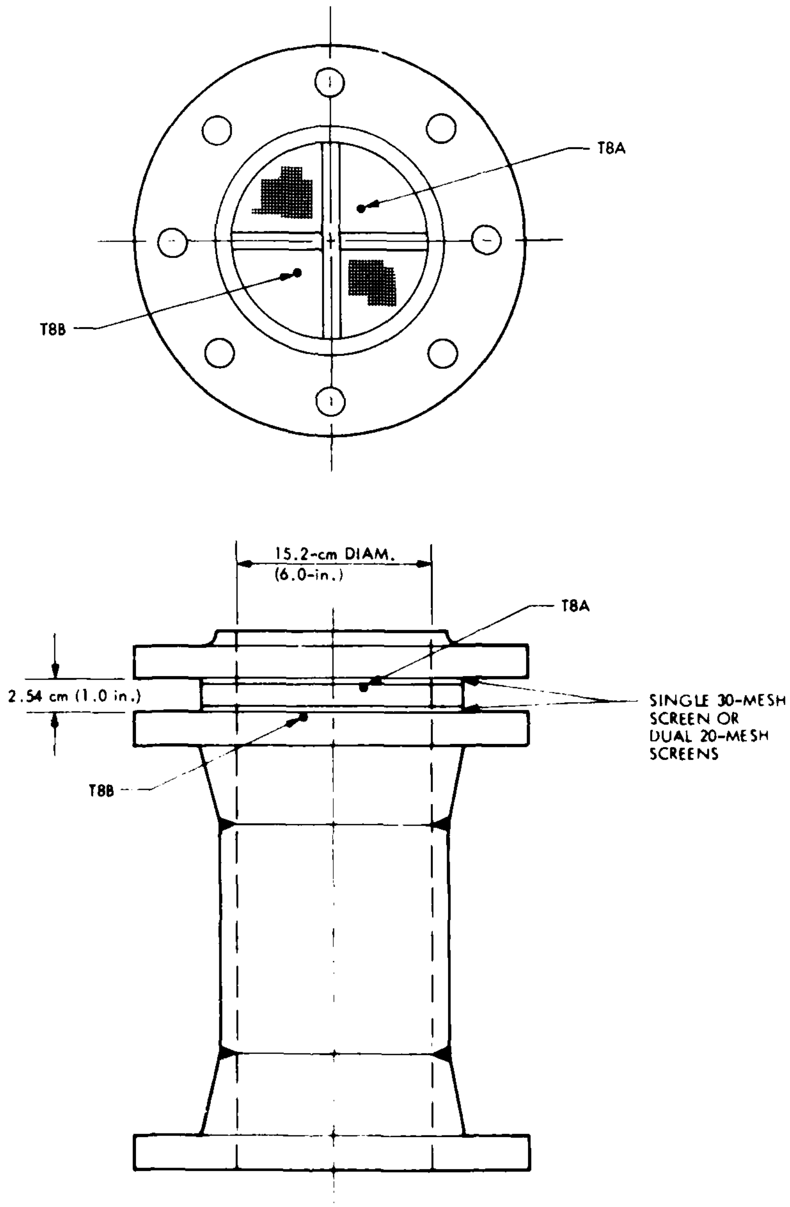



Figure 9-[illegible]. Screen-Type Arrester Test Assembly, 15.2-cm Diameter, Schematic Drawing

that the screen temperature varies inversely with the flow-through velocity, as would be expected. The one-third lower flow-through velocity of this larger screen surface resulted in soak-back temperatures three times higher than the smaller screen noted above in paragraph A-1 of this section. The propane/air

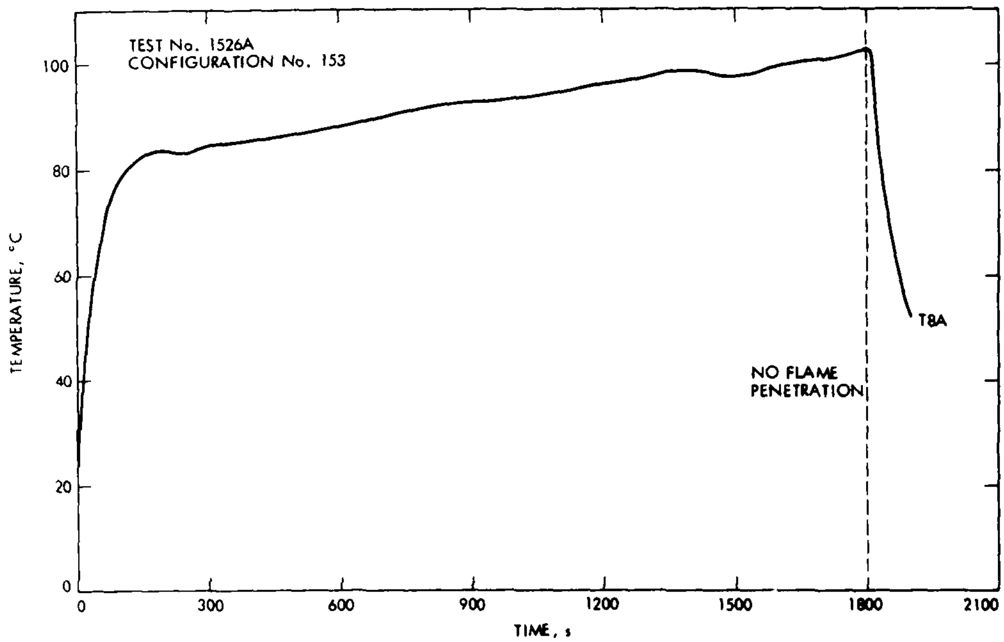



Figure 9-3. Single 30-Mesh Screen Arrester, 15.2-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

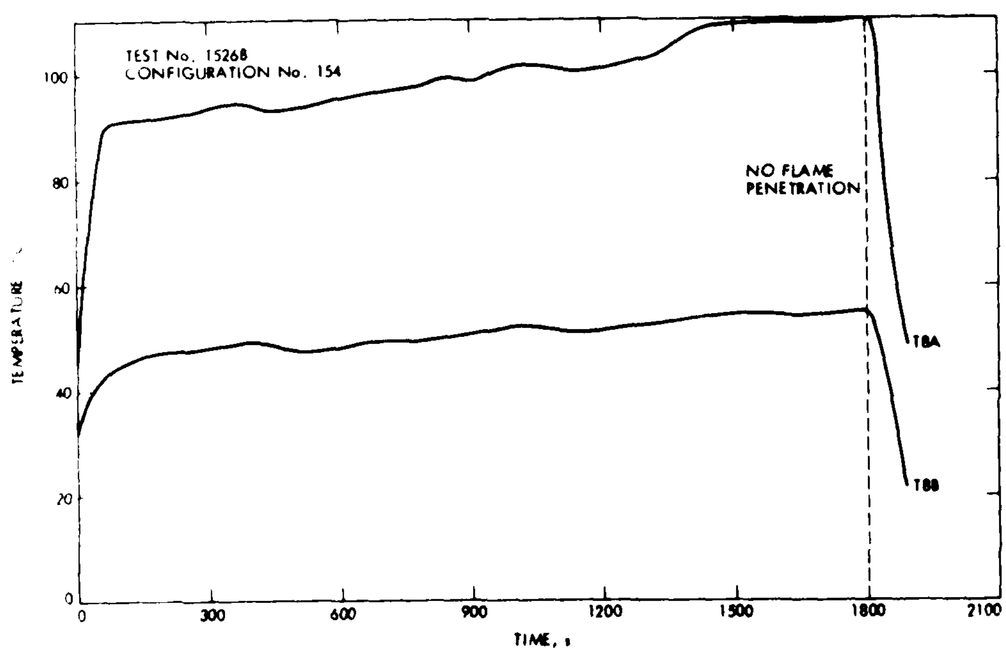



Figure 9-4. Dual 20-Mesh Screen Arrester, 15.2-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

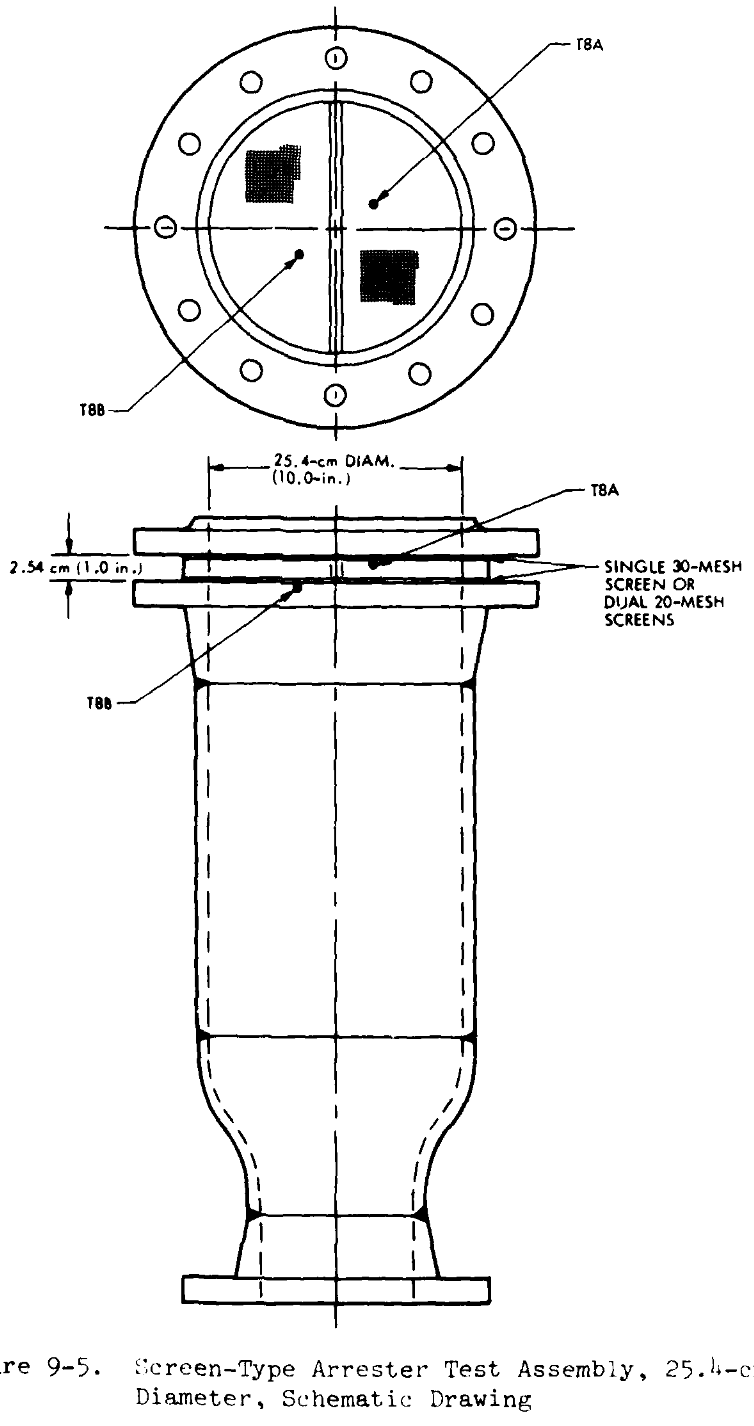



Figure 9-5. Screen-Type Arrester Test Assembly, 25.4-cm Diameter, Schematic Drawing

mixture flame did not penetrate through this single 30-mesh screen arrester. A plot of the test results is presented in Figure 9-6. Posttest inspection revealed only slight discoloration of the wire mesh over about 60% of the surface area as shown in Figure 9-7.

4. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter

A schematic drawing of this arrester test assembly (Test Configuration No. 156), presented in Figure 9-5, shows the location of the thermocouples (T8A and T8B) used to measure the two screens' temperatures. The approaching flow velocity in the 25.4-cm- (10-in.-) diameter pipe was 0.56 m/s (1.8 ft/s) and the flow-through velocity in the screens was 1.21 m/s (3.96 ft/s). The temperature on the downstream screen (T8A) reached an initial plateau value of 160°C (320°F) after 120 seconds of operation and then increased to a nominal value of 190°C (374°F) for the remaining 30 minutes of operation. The upstream screen temperature (T8B) reached 60°C (140°F) after 60 seconds and then slowly increased to 70°C (158°F) by the end of test. The propane/air mixture flame did not penetrate through this dual 20-mesh screen arrester. A plot of the test results is presented in Figure 9-8.

The maximum temperature for this 20-mesh screen arrester assembly was expected to be higher than that measured on the similar sized 30-mesh screen arrester, because of the lower flow-through velocity. Posttest inspection revealed that the thermocouple (T8A) was making poor contact with the screen surface and was located in an area of low temperature, as indicated by the flame impingement pattern on the screen. There was no damage to the screens other than a discoloration covering about 60% of the flow area on the downstream wire mesh. A posttest photograph of the 20-mesh screens and spacer is presented in Figure 9-9.

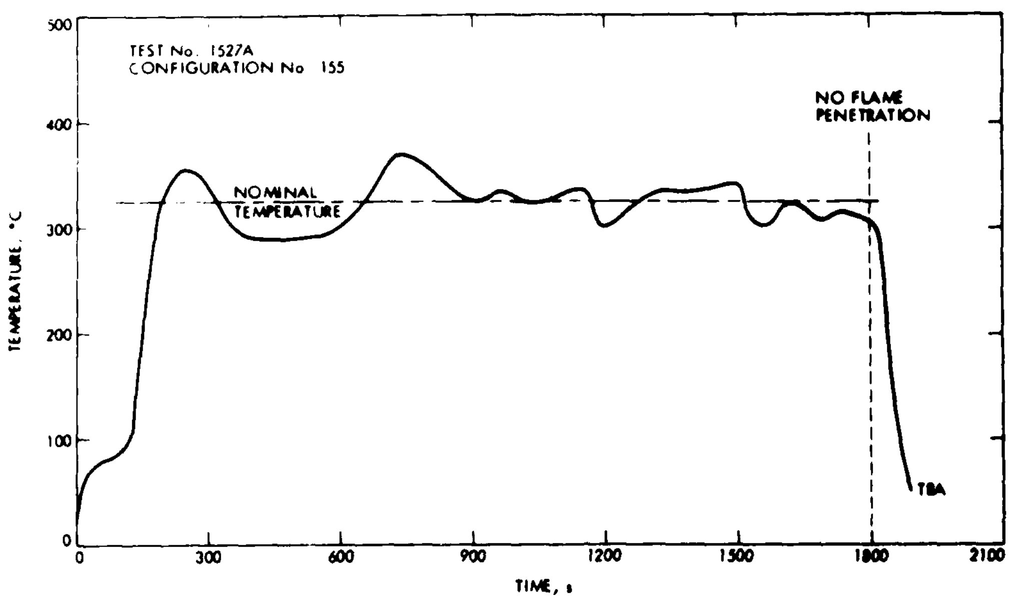



Figure 9-6. Single 30-Mesh Screen Arrester, 25.4-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

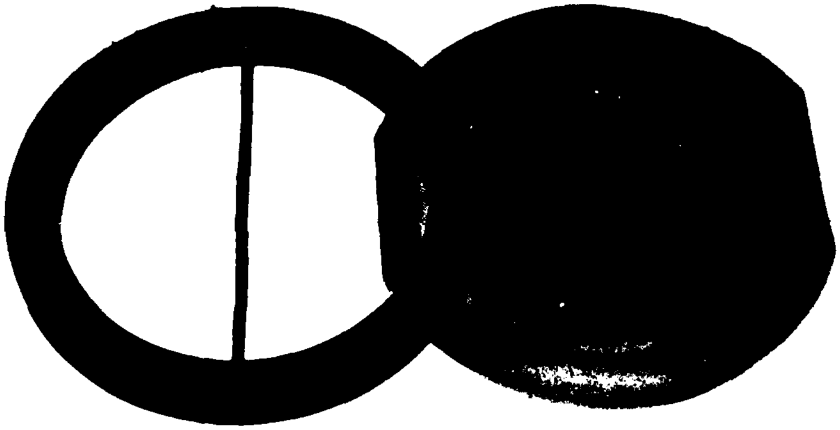


Figure 9-7. Single 30-Mesh Screen Arrester, 25.4-cm Diameter, Posttest

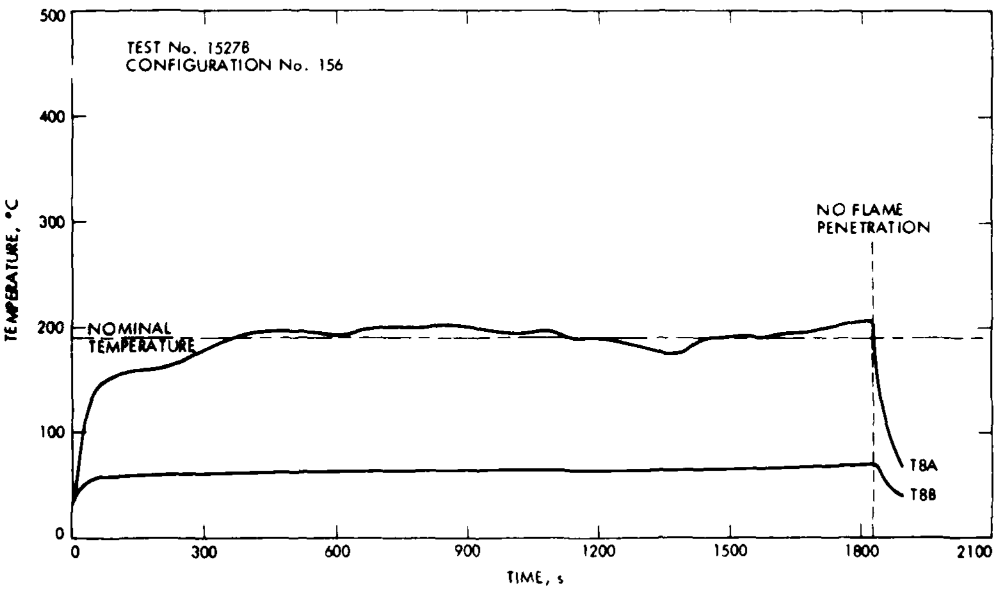



Figure 9-8. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter, Propane/Air Mixture Sustained Burning Test Results

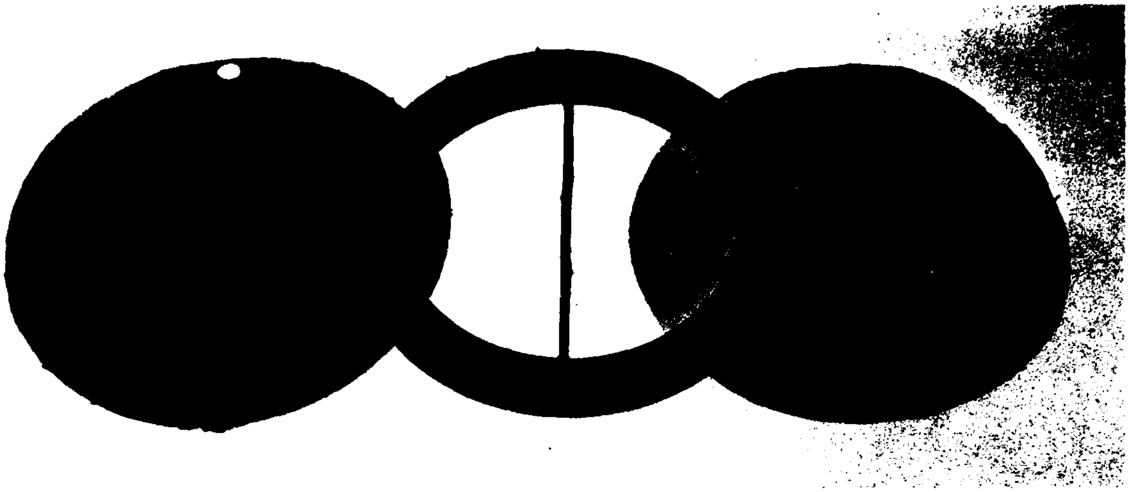
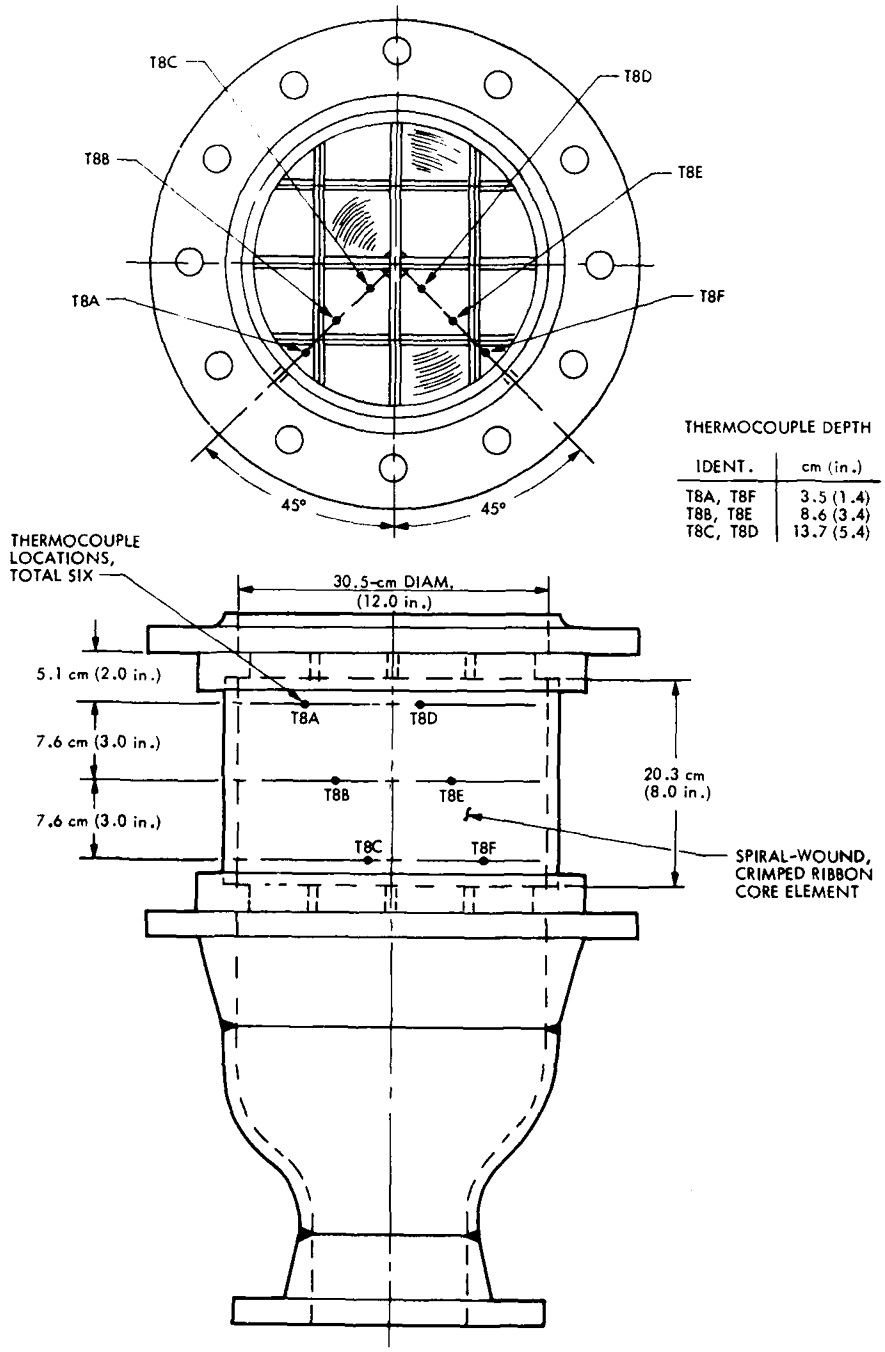


Figure 9-9. Dual 20-Mesh Screen Arrester, 25.4-cm Diameter, Posttest

5. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester

A schematic drawing of this arrester test assembly (Test Configuration No. 149), presented in Figure 9-10 shows the location of the six thermocouples (T8A to T8F) used to measure the crimped ribbon core element temperature. The approaching flow velocity in the 30.5-cm- (12-in.-) diameter pipe was 0.39 m/s (1.28 ft/s) and the flow-through velocity in the crimped ribbon core element was 0.45 m/s (1.46 ft/s). Temperature at the downstream center of the core element ([illegible]) reached a maximum value of 1000°C (1832°F) after 900 seconds of operation and then slowly decreased to 930°C (1706°F) at the end of the 30 minutes (1800 seconds). The sustained flame had to be burning inside the core element to produce this high temperature, which is considerably above the spontaneous ignition temperature of 504°C (940°F) for the propane/air mixture. The center of the core element (T8B) reached this spontaneous ignition temperature just [illegible] seconds before test termination. It appears that the sustained flame was initially confined to the center portion of the downstream face, and after [illegible] seconds of operation, the flame had expanded to the outer perimeter (T8A). The propane/air mixture flame did not penetrate through this spiral-wound, crimped stainless-steel arrester during the 30-minute test duration. However, the core element had not reached a state of thermal equilibrium and there is considerable evidence of continuing flame propagation into the core. It is quite likely that the arrester would have eventually failed. A plot of the test results is presented in Figure 9-11.

Posttest inspection of this arrester test assembly revealed some minor damage to the core element in the form of distortion and discoloration to the stainless-steel ribbon windings. The retainer grid was also distorted from restricted thermal expansion and some grid elements were broken at the weld joints. A posttest photograph of the downstream end of the arrester assembly is presented in Figure 9-12.




THERMOCOUPLE DEPTH

| IDENT. | cm (in.) |
|---|---|
| T8A, T8F | 3.5 (1.4) |
| T8B, T8E | 8.6 (3.4) |
| T8C, T8D | 13.7 (5.4) |

Figure 9-10. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Test Assembly Schematic Drawing

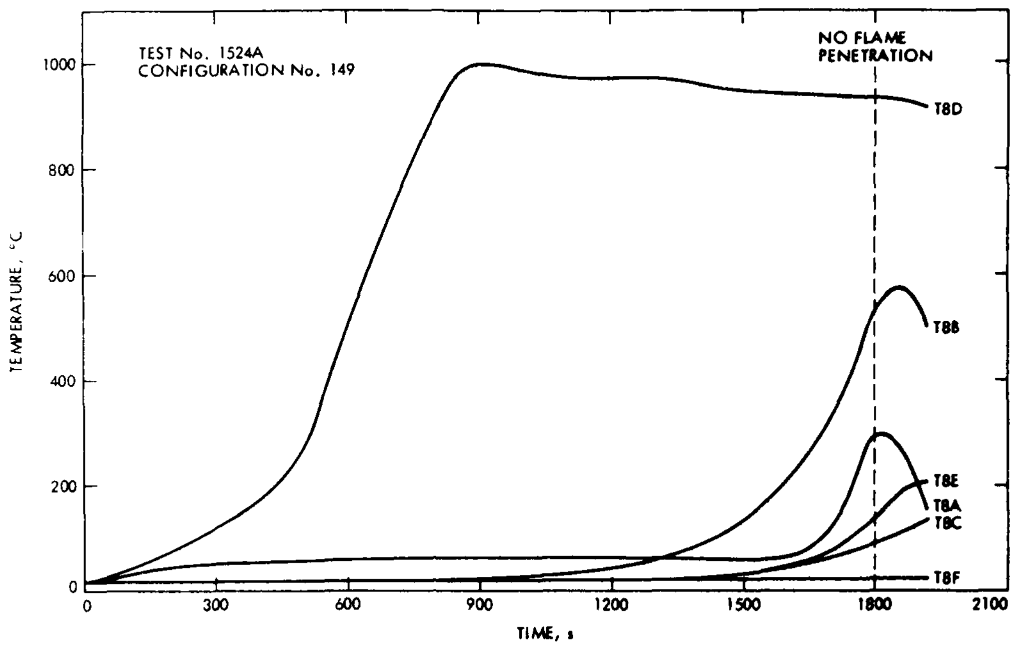
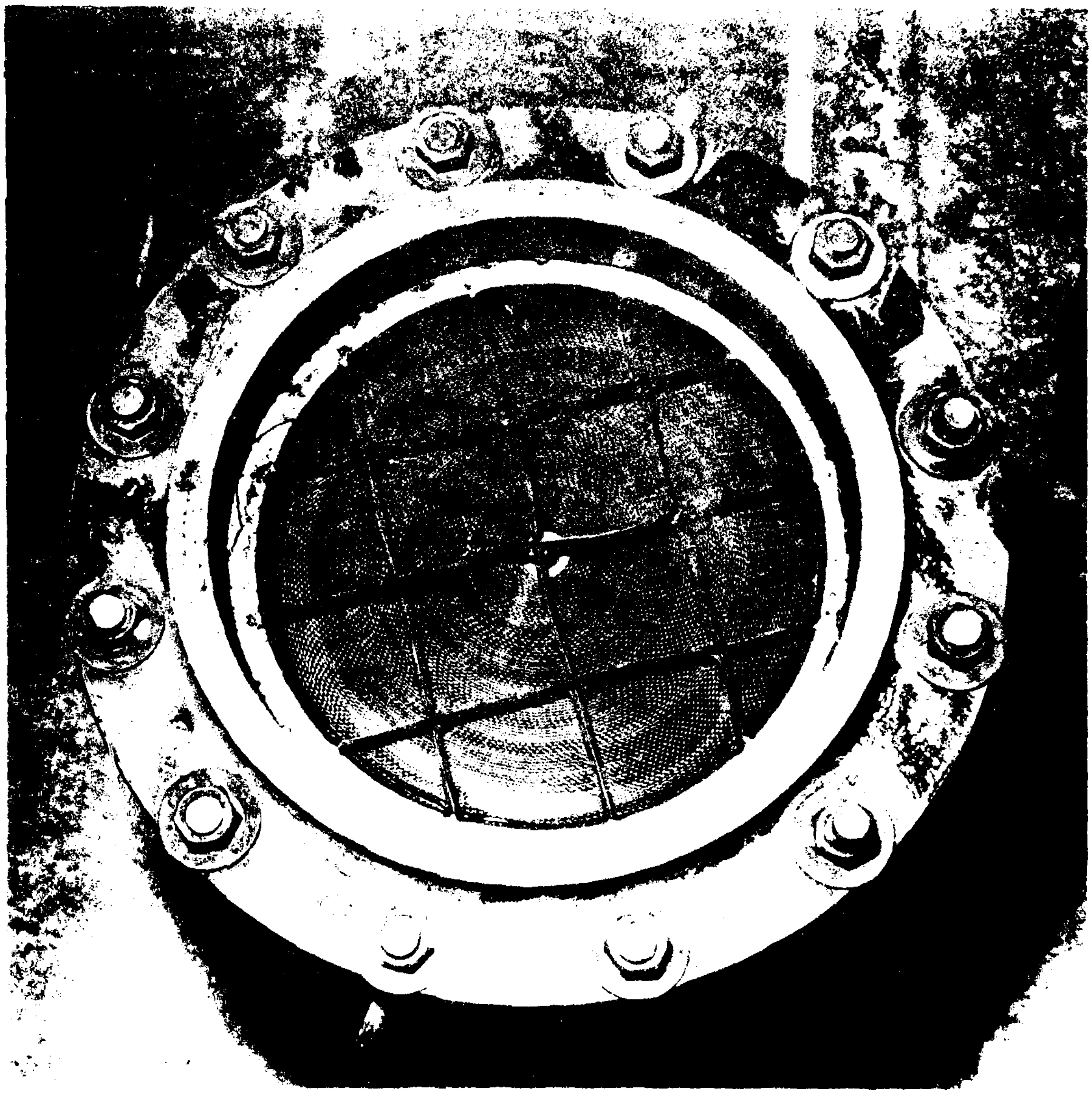



Figure 9-11. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Propane/Air Mixture Sustained Burning Test Results

6. Packed Bed of Aluminum Ballast Rings Arrester

A schematic drawing of this arrester test assembly (Test Configuration No. 151), presented in Figure 9-13, shows the location of seven thermocouples (T8A to T8G) used to measure the temperature in the bed of rings and on the single 30-mesh screen retainer. The approaching flow velocity in the 25.4-cm-(10-in.-) diameter pipe was 0.56 m/s (1.8 ft/s), the flow-through velocity in the bed of rings is estimated at 0.94 m/s (3.1 ft/s), and the flow-through velocity in the 30-mesh screen was 1.5 m/s (4.9 ft/s). Temperature of the screen (T8G) reached the nominal value of 350°C (662°F) after 200 seconds of operation and held fairly steady for the 30 minutes duration. The temperatures at the top of the bed (T8A and T8D) increased slightly to a maximum of 125°C (257°F) due to radiation only; very little conductive and no convective heating was possible. The lower part of the bed remained at the nominal mixture inlet temperature of 50°C (122°F). The propane/air mixture flame did not penetrate through the 30-mesh retainer screen on the packed bed of rings during the 30-minute test duration. A plot of the test results is shown in Figure 9-14. Posttest inspection revealed only a slight downstream bowing and discoloration of the retainer grid and screen as shown in Figure 9-15.



AD-A100 040 JET PROPULSION LAB PASADENA CA F/G 21/2
FLASHBACK FLAME ARRESTER DEVICES FOR FUEL CARGO TANK VAPOR VENT--ETC(U)
MAR 81 R A BJORKLUND, R O KUSHIDA DOT-CG-Z-70099-8-85
UNCLASSIFIED JPL-PUB-81-10 USCG-D-20-81 NL

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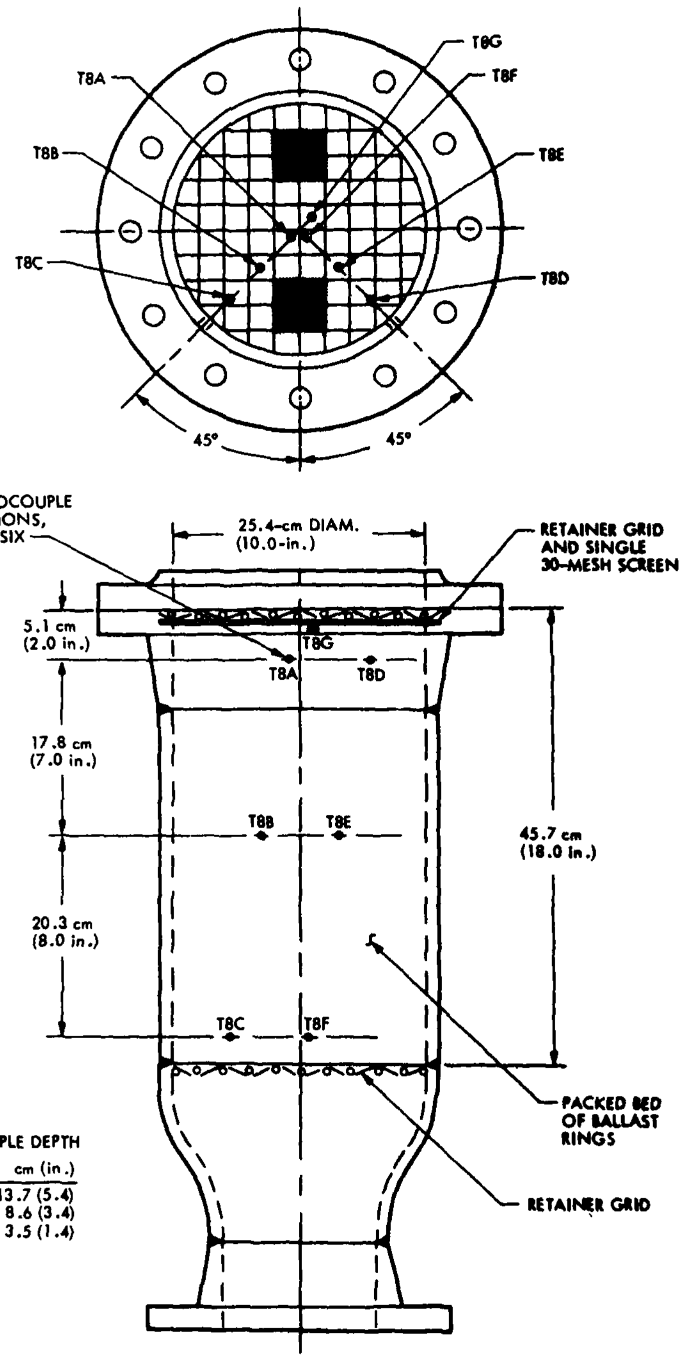



| IDENT. | cm (in.) |
|---|---|
| T8A, T8F | 13.7 (5.4) |
| T8B, T8E | 8.6 (3.4) |
| T8C, T8D | 3.5 (1.4) |

Figure 9-13. Packed Bed of Aluminum Ballast Rings with Single 30-Mesh Screen Arrester Test Assembly Schematic Drawing

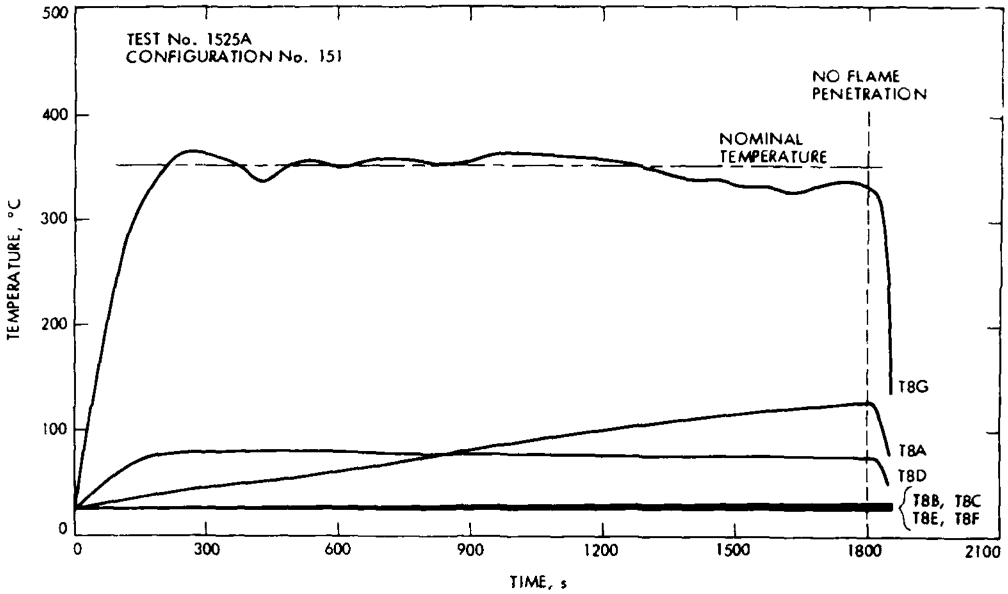



Figure 9-14. Packed Bed of Aluminum Ballast Rings with Single 30-Mesh Screen Arrester Propane/Air Mixture Sustained Burning Test Results

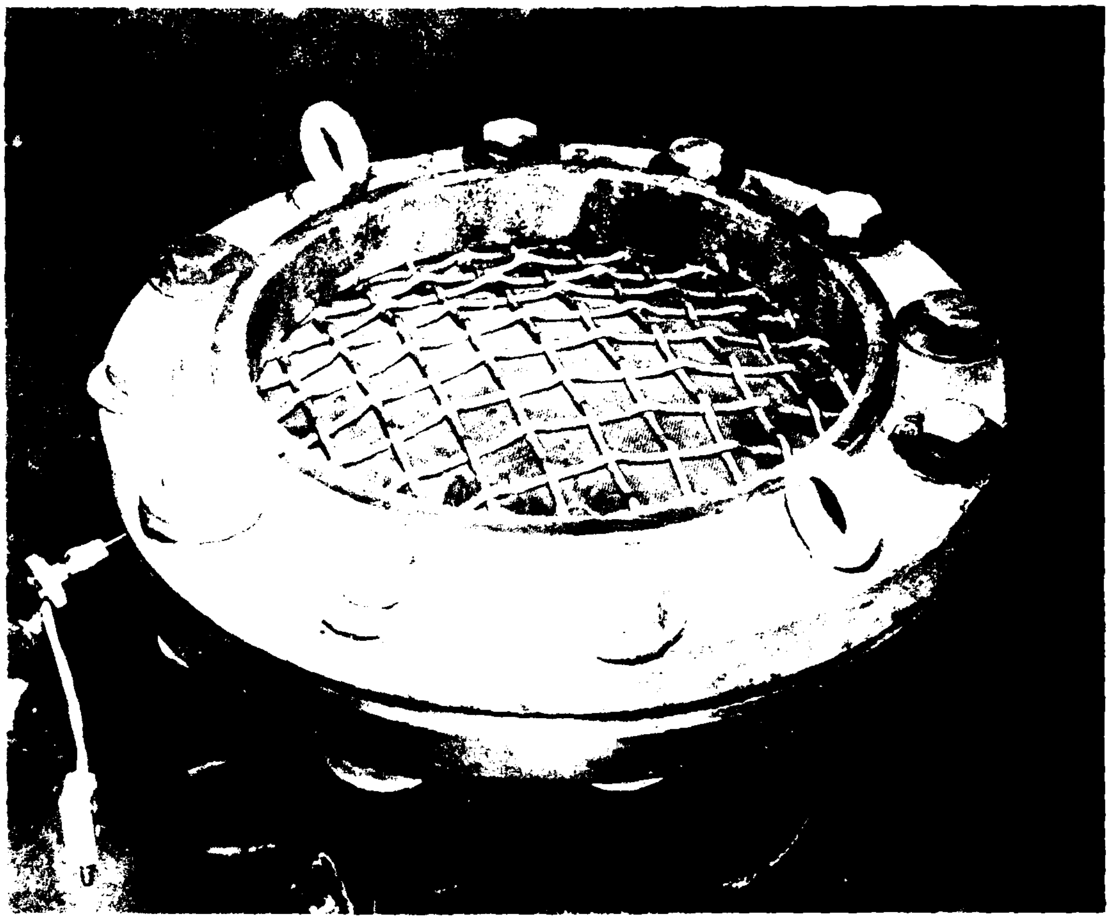
B. ETHYLENE/AIR MIXTURE TESTS

This last series of sustained burning tests were made with ethylene/air mixture at standard test conditions where the injection equivalence ratio was 1.15 (A/F = 12.86). The planned test duration was 30 minutes. Only the two arrester configurations of the NASA funded program were tested: (1) the spiral-wound, crimped stainless-steel ribbon arrester, and (2) the packed bed of aluminum Ballast rings. The USCG funded program did not require sustained burning tests with ethylene/air mixtures because the test conditions were considered to be too severe for screen-type flame arresters.

The following results are for the ethylene/air mixture sustained burning tests. A tabular summary of the test data is presented in Appendix E.

1. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester

This is the same arrester test assembly (Test Configuration No. 150) shown in Figure 9-10. The test flow conditions were the same as those described in Paragraph A-5 of this section. On the first test (No. 1524B) the flame penetrated into the core (T8A and T8E) after only 60 seconds of operation and reached a high temperature of around 900°C (1652°F) at 150 seconds. The flame spread to the outer perimeter of the core (T8B and T8D) increasing this area temperature to



[illegible] with [illegible]

[illegible] through [illegible] was terminated. [illegible] were [illegible] mixture of [illegible] test [illegible] windings [illegible]

[illegible] with [illegible] identical [illegible] results is [illegible] the [illegible]

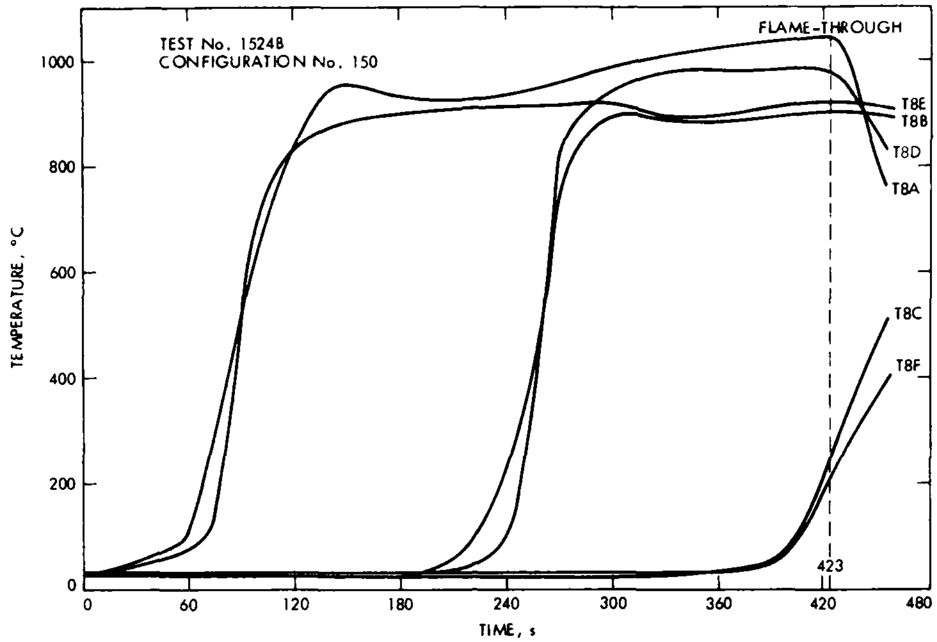



Figure 9-16. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning First Test Results

2. Packed Bed of Aluminum Ballast Rings Arrester

This is the same arrester test assembly (Test Configuration No. 152) shown in Figure 9-13. The test flow conditions were the same as those described in Paragraph A-6 of this section. In the first test (No. 1525B) the temperature on the upstream face of the retainer screen (T8G) increased rapidly, reaching the spontaneous ignition level of 490°C (914°F) after only 35 seconds of operation. Flame penetration occurred at 43 seconds when the screen temperature reached 560°C (1040°F). The bed of aluminum Ballast rings remained at the inlet ethylene/air mixture temperature with only the downstream center of the bed (T8A) receiving any measurable radiation from the sustained burning. Flame penetration through the retainer screen was followed by a detonation in the inlet piping. Flame speeds measured in the witness section, which was just upstream of the test arrester section, were at the detonation velocity of around 1830 m/s (6000 ft/s). This would indicate that the penetrating flame had made the transition from deflagration to detonation within the length of the packed bed arrester. A plot of the test results is presented in Figure 9-18. Posttest inspection of the arrester revealed some distortion and discoloration of the retainer grid and screen assembly caused by internal pressure developed during the detonation.

The above test was repeated at the same test conditions and with the same arrester test assembly. This second test (No. 1525C) resulted in a detonation immediately after ignition. Posttest disassembly and inspection of the packed bed arrester revealed that the screen retainer had been impacted in several

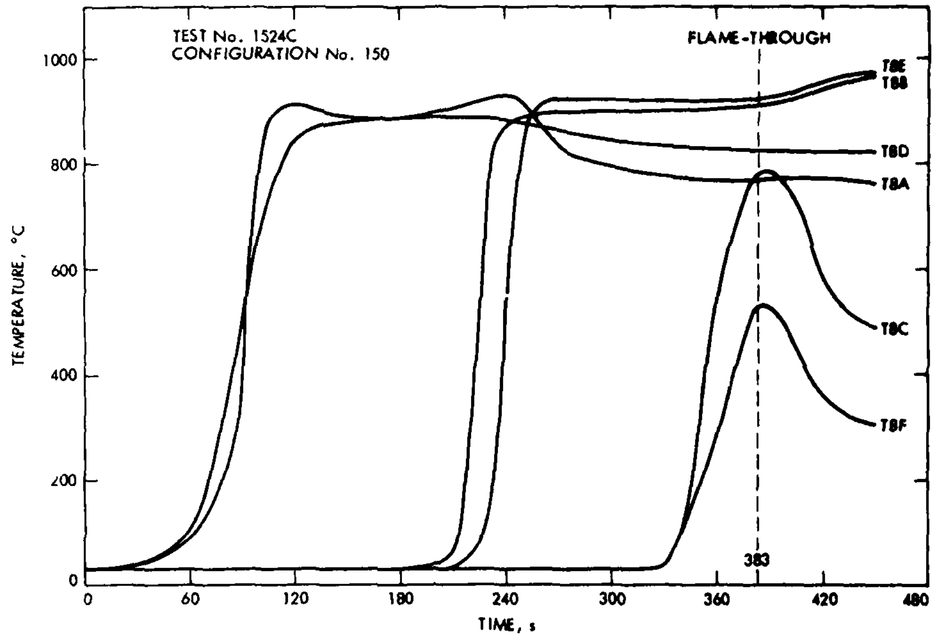



Figure 9-17. Spiral-Wound, Crimped Stainless-Steel Ribbon Arrester Ethylene/Air Mixture Sustained Burning Second Test Results

places by Ballast rings causing punctures as shown in Figure 9-19. The undetected damage to the screen was probably initiated to a lesser extent during the first sustained burning test that resulted in a detonation. These small punctures allowed flame penetration without heat-up on the second test and the subsequent detonation enlarged the holes to the size shown.

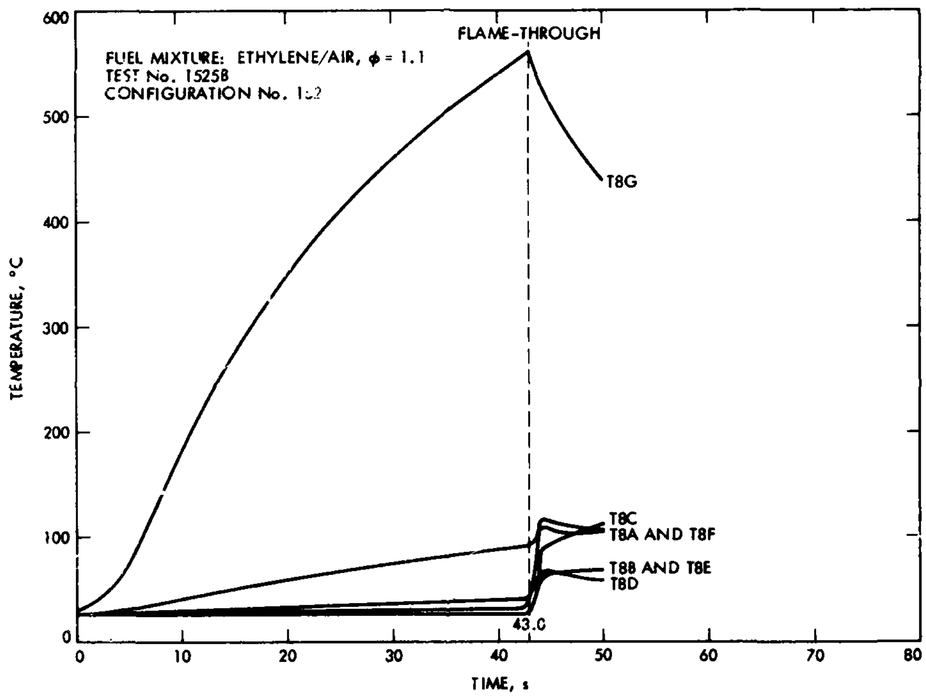
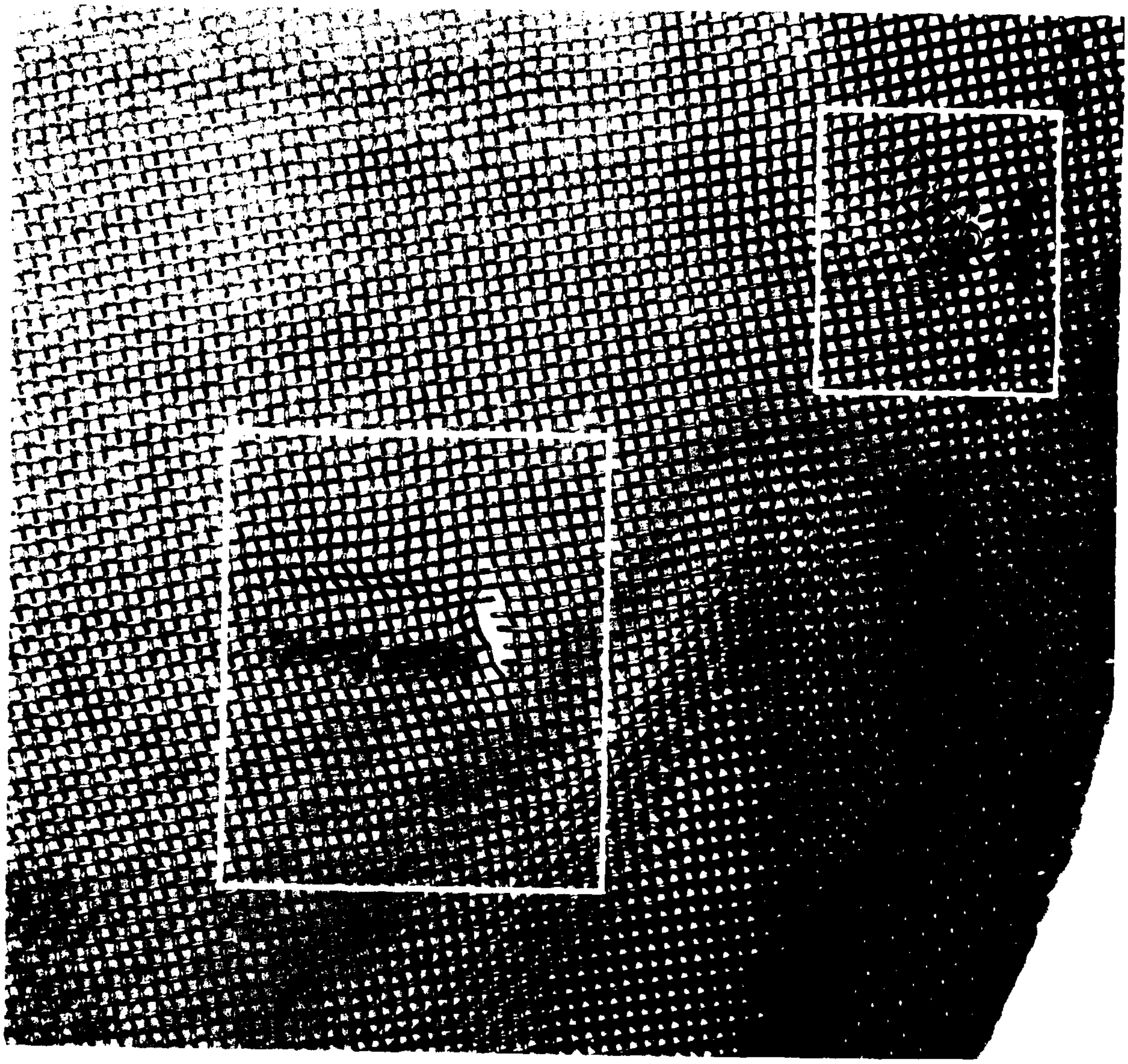



Figure 9-18. Packed Bed of Ballast Rings with Single 30-Mesh Screen Arrester Ethylene/Air Sustained Burning Test Results



## SECTION X

## CONCLUSIONS

The following conclusions have been reached from the test results of this experimental evaluation of flame arrester devices in a simulated fuel storage tank vent stack installation discharging eight types of combustible fuel/air mixtures, including: (1) propane, (2) ethylene, (3) gasoline, (4) methanol, (5) toluene, (6) diethyl ether, (7) butane, and (8) acetaldehyde. The test flame arresters were mounted on the end of a 15.2-cm- (6-in.-) diameter pipe vent located in an unconfined one-atmosphere environment. The standard test condition used an injection equivalence ratio from 1.0 to 1.2 to produce the theoretical maximum flame speed for the particular fuel/air mixture in use; the fuel/air mixture temperature ranged from 10 to 38°C (50 to 100°F), and the inlet piping nominal flow velocity was 1.52 m/s (5 ft/s).

(1) An ignition source upstream near the flame arrester and in the center of the exhaust plume produced the highest flashback flame speed for a flame propagating upstream in the direction of the arrester.

(2) Ethylene/air mixture produced the highest average flashback flame speed of 6.60 m/s (21.65 ft/s), ranging from 4.86 to 10.66 m/s (15.94 to 34.98 ft/s).

(3) Butane/air mixture produced the lowest average flashback flame speed of 3.62 m/s (11.88 ft/s), ranging from 2.92 to 4.25 m/s (9.58 to 13.94 ft/s).

(4) Flashback flames from the typical bulk cargo fuels tested will propagate in an open environment, such as the deck of a transport vessel, but will not produce a detonation unless they penetrate an opening leading into a fuel cargo tank.

(5) The single 30-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested.

(6) The dual 20-mesh stainless-steel screen arrester was effective in quenching flashback flames from all eight fuel/air mixtures tested except the ethylene/air mixture, where the flame speed was 4.86 m/s (15.94 ft/s) or faster.

(7) Damage to a screen flame arrester from a puncture, tear, or corrosion that results in holes larger than the original mesh size renders the screen useless in quenching a flashback flame. The damaged screen should be replaced to restore the arrester's effectiveness.

(8) The spiral-wound, crimped stainless-steel ribbon arrester was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(9) The packed bed of aluminum Ballast rings arrester with single 30-mesh stainless-steel screen retainers was effective in quenching flashback flames from the propane, ethylene, and gasoline fuel/air mixtures tested, and would probably quench the other five fuel/air mixtures listed.

(10) The packed bed of aluminum Ballast rings arrester without the single 30-mesh screen retainer was not effective in quenching flashback flames from gasoline/air mixtures, and would probably not quench the other seven fuel/air mixtures listed.

(11) The test configurations for the single 30-mesh screen arrester, the dual 20-mesh screen arrester, the spiral-wound, crimped ribbon arrester, and the packed bed of Ballast rings arrester withstood all flashback flame testing without any structural damage and only slight discoloration from the short duration of flame impingement (approximately 25 seconds).

(12) The single 30-mesh screen arrester and the dual 20-mesh screen arrester withstood flames from propane/air mixtures for 30 minutes without structural damage and only slight discoloration of the screen wire. The fuel/air mixture flow velocity through the openings in the screen ranged from 1.2 to 4.1 m/s (3.9 to 13.5 ft/s), depending on the size of the arrester test assembly. In each configuration, the screens reached a condition approaching thermal equilibrium after approximately 400 seconds where the temperature was well below the spontaneous ignition temperature for the propane/air mixture. It is concluded that the sustained burning conditions on these arresters could have continued for an indefinite period of time.

(13) The equilibrium temperature on the surface of a screen flame arrester at sustained burning conditions is a function of flow velocity of the fuel/air mixture passing through the screen; the lower the velocity, the higher the equilibrium temperature. It is possible that at very low flow-through velocities the temperature of the screen would increase to the spontaneous ignition temperature of the fuel and the flame could penetrate the screen arrester.

(14) The spiral-wound, crimped ribbon arrester withstood flames from the propane/air mixture for 30 minutes. During this time, the flame propagated into part of the depth of the core element, causing distortion and discoloration of the stainless-steel ribbon. Thermal equilibrium within the core element was not achieved during the 30 minutes of testing as the temperatures measured inside the ribbon windings continued to increase above the spontaneous ignition temperature for propane/air mixtures. It is concluded that the flame would have eventually penetrated the arrester, given sufficient time. Sustained burning from the ethylene/air mixture did penetrate through this arrester on two tests of 423 and 383 seconds. Therefore, the ability of this type of flame arrester to withstand sustained burning is highly dependent on the flame speed and the spontaneous ignition temperature of the fuel/air mixture.

(15) The packed bed of Ballast rings arrester with a single 30-mesh screen retainer withstood flames from the propane/air mixture for 30 minutes. The results were very similar to those obtained from the single 30-mesh screen arrester, and it is apparent that the bed of rings has little or no influence on the performance of this arrester configuration. Sustained burning from the ethylene/air mixture did penetrate through this arrester in only 43 seconds on one test, resulting in a deflagration-to-detonation transition within the bed of rings. The retainer screen was damaged by impacts from the bed of rings, and this damage allowed the flame to penetrate immediately after ignition on a repeat test. It is concluded that the packed bed of rings arrester with a single 30-mesh screen is no more effective than a single 30-mesh screen in withstanding and quenching flashback flames.

SECTION XI

RECOMMENDATIONS

Based upon the results of this test program, the following recommendations are made regarding the selection and installation of flame arresting devices on fuel storage tank vent stacks in a marine environment:

(1) Based upon flame quenching capability, structural durability, and a low susceptibility to corrosion and fouling, the following flame arrester devices have been found effective in preventing flashback flames in an open environment from entering vent openings of a cargo tank containing typical bulk fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless steel ribbon, and (4) packed bed of aluminum Ballast rings with single 30-mesh stainless-steel screen retainers. Ethylene, which is a gas at ambient temperature and pressure, is not a typical bulk cargo fuel.

(2) Based upon the ability to withstand 30 minutes of continuous burning of a propane/air mixture, the following flame arrester devices have been found effective in sustaining the flame from typical bulk cargo fuels: (1) single 30-mesh stainless-steel screen, (2) dual 20-mesh stainless-steel screen, (3) spiral-wound, crimped stainless-steel ribbon, and (4) packed bed of Ballast rings with single 30-mesh stainless steel screen retainers. Spiral-wound, crimped metal ribbon arresters appear to have a finite time duration for sustained burning conditions, and should therefore be evaluated for the specific fuel and at the most severe condition of the intended applications. None of the flame arrester devices tested is effective in sustaining the flame from an ethylene/air mixture for 30 minutes duration.

(3) Based upon the inverse relationship between the equilibrium temperature of a screen flame arrester at sustained burning conditions and the fuel/air mixture flowthrough velocity, it is recommended that in fuel transfer operations the rate of fuel flow should be fast enough to keep the exhaust velocity of vented flammable mixture well above the laminar burning velocity of the fuel being transferred. In the event of a flashback flame, this safety precaution will aid in keeping the screen flame arrester on the vent from over-heating by a sustained flame.

(4) The selection of a location for the flame arrester device on the vent stack should be limited to the very end of the pipe. The flame quenching ability of the arrester is reduced by any length of pipe, housing, or mechanical device downstream of the arrester. Screen-type flame arresters are effective only if they are undamaged by punctures or tears in the wire mesh and there are no gaps or holes around the periphery larger than the openings specified for the 20- or 30-mesh screen. All flame arrester devices should be periodically inspected for damage and cleaned to remove fouling and corrosion.

(5) The selection of materials used in the construction of arresters should be based on their compatibility with the local environment and the fuel vapors to be encountered. However, stainless steel is recommended.

The data and experience obtained from these flashback flame and sustained burning tests is limited to those fuel and air mixtures tested in a 15.2-cm- (16-in.-) diameter pipe size. It is recommended that extrapolation of this data should be limited to the following:

(1) Application to other fuels should be limited to those hydrocarbon fuels that have similar combustion characteristics to those fuels tested.

(2) Applications scaled down to pipe sizes smaller than 15.2-cm (6-in.) diameter are considered to be conservative.

(3) Scaled-up applications should be limited to pipe sizes no larger than a 20.3-cm (8-in.) diameter, providing adequate consideration is given to structural strength.

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## APPENDIX A

### TEST CONFIGURATION LOG

| Configuration No. | Test No. | Description |
|---|---|---|
| 100 to 112 | 1488 to 1495 | The first thirteen test configurations were evolved during the facility checkout tests. They included the preliminary installation of a subscale flame chamber that was later replaced by the full-scale flame chamber and the exhaust collector burn stack. Flame sensors on the flame chamber outer wall were repositioned from the horizontal center line to the top center line. Three igniter positions used in the flame chamber were (1) upstream, (2) middle, and (3) downstream. An aluminum flame shield was installed on the inlet piping upstream of the flame arrester test section. Also, a second aluminum flame shield was installed in front of the downstream flame chamber frangible diaphram. Fuels used on these checkout tests were gasoline and commercial grade propane. The test arresters included both the dual 20-mesh screens and the single 30-mesh screen. |
| 113 | 1496 (A-C) | This test configuration is shown in Figure 7-2.<br>Flame arrester: dual 20-mesh screens<br>Fuel: propane<br>Igniter position: upstream |
| 114 | 1497 (A-C) | Flame arrester: dual 20-mesh screens<br>Fuel: propane<br>Igniter position: downstream |
| 115 | 1498 (A-D) | Flame arrester: single 30-mesh screen<br>Fuel: propane<br>Igniter position: downstream |
| 116 | 1499 (A-C) | Flame arrester: single 30-mesh screen<br>Fuel: propane<br>Igniter position: upstream |
| 117 | 1500 (A-C) | Flame arrester: single 30-mesh screen<br>Fuel: ethylene<br>Igniter position: upstream |
| 118 | 1501 (A) | Changed the exhaust collector burn-stack flame arrester from an Amal spiral-wound, crimped stainless-steel ribbon to a Shand and Jurs spiral-wound, crimped aluminum ribbon assembly.<br>Flame arrester: single 30-mesh screen<br>Fuel: ethylene<br>Igniter position: upstream |

| Configuration No. | Test No. | | Description |
|---|---|---|---|
| 119 | 1501 (B-D) | Flame arrester:<br>Fuel:<br>Igniter position: | single 30-mesh screen<br>ethylene<br>downstream |
| 120 | 1502 (A) | Flame arrester:<br>Fuel:<br>Igniter position: | none<br>ethylene<br>downstream |
| 121 | 1502 (B-D) | Flame arrester:<br>Fuel:<br>Igniter position: | dual 20-mesh screens<br>ethylene<br>downstream |
| 122 | 1503 (A-C) | Flame arrester:<br>Fuel:<br>Igniter position: | dual 20-mesh screens<br>ethylene<br>upstream |
| 123 | 1504 (A-C) | Flame arrester:<br>Fuel:<br>Igniter position: | crimped ribbon<br>propane<br>upstream |

NOTE: All of the following tests were made with the igniter located in the upstream position unless otherwise noted.

| | | | |
|---|---|---|---|
| 124 | 1505 (A-D) | Flame arrester:<br>Fuel: | crimped ribbon<br>ethylene |
| 125 | 1506 (A-D) | Flame arrester:<br>Fuel: | crimped ribbon<br>gasoline |
| 126 | 1507 (A-D) | Flame arrester:<br>Fuel: | none<br>gasoline |
| 127 | 1507 (C)<br>1508 (A-B) | Flame arrester:<br>Fuel: | single 30-mesh screen<br>gasoline |
| 128 | 1508 (C-E) | Flame arrester:<br>Fuel: | dual 20-mesh screens<br>gasoline |
| 129 | 1509 (A-C) | Flame arrester:<br>Fuel: | packed bed of rings<br>gasoline |
| 130 | 1510 (A-C) | Flame arrester:<br>Fuel: | packed bed of rings with single 30-mesh screen<br>gasoline |

| Configuration No. | Test No. | Description | |
|---|---|---|---|
| 131 | 1511 (A-D) | Flame arrester: | packed bed of rings with single 30-mesh screen |
| | | Fuel: | ethylene |
| 132 | 1512 (A-C) | Flame arrester: | packed bed of rings with single 30-mesh screen |
| | | Fuel: | propane |
| 133 | 1513 (A-C) | Flame arrester: | single 30-mesh screen |
| | | Fuel: | methyl alcohol |
| 134 | 1513 (D) | Flame arrester: | none |
| | | Fuel: | methyl alcohol |
| 135 | 1514 (A-C) | Flame arrester: | dual 20-mesh screens |
| | | Fuel: | methyl alcohol |
| 136 | 1515 (A-C) | Flame arrester: | dual 20-mesh screens |
| | | Fuel: | toluene |
| 137 | 1515 (D) | Flame arrester: | none |
| | | Fuel: | toluene |
| 138 | 1516 (A-D) | Flame arrester: | single 30-mesh screen |
| | | Fuel: | toluene |
| 139 | 1517 (A-C) | Flame arrester: | single 30-mesh screen |
| | | Fuel: | diethyl ether |
| 140 | 1517 (D) | Flame arrester: | none |
| | | Fuel: | diethyl ether |
| 141 | 1518 (A-C) | Flame arrester: | dual 20-mesh screens |
| | | Fuel: | diethyl ether |
| 142 | 1519 (A-D) | Flame arrester: | dual 20-mesh screens |
| | | Fuel: | butane |
| 143 | 1519 (E) | Flame arrester: | none |
| | | Fuel: | butane |
| 144 | 1520 (A-C) | Flame arrester: | single 30-mesh screen |
| | | Fuel: | butane |
| 145 | 1521 (A-C) | Flame arrester: | single 30-mesh screen |
| | | Fuel: | acetaldehyde |

| Configuration No. | Test No. | Description | |
|---|---|---|---|
| 146 | 1521 (D) | Flame arrester: | none |
| | | Fuel: | acetaldehyde |
| 147 | 1522 (A-C) | Flame arrester: | dual 20-mesh screens |
| | | Fuel: | acetaldehyde |
| 148 | 1523 (A-B) | Changed the test assembly to the sustained burning test configuration. | |
| | | Flame arrester: | crimped ribbon |
| | | Fuel: | propane |
| 149 | 1524 (A) | Changed the thermocouples in the test arrester from open tip ungrounded to closed-end grounded. | |
| | | Flame arrester: | crimped ribbon |
| | | Fuel: | propane |
| 150 | 1524 (B-C) | Flame arrester: | crimped ribbon |
| | | Fuel: | ethylene |
| 151 | 1525 (A) | Flame arrester: | packed bed of rings with single 30-mesh screen |
| | | Fuel: | propane |
| 152 | 1525 (B-C) | Flame arrester: | packed bed of rings with single 30-mesh screen |
| | | Fuel: | ethylene |
| 153 | 1526 (A) | Flame arrester: | 15.2-cm- (6.0-in.-) diameter single 30-mesh screen |
| | | Fuel: | propane |
| 154 | 1526 (B) | Flame arrester: | 15.2-cm- (6.0-in.-) diameter dual 20-mesh screens |
| | | Fuel: | propane |
| 155 | 1527 (A) | Flame arrester: | 25.4-cm- (10.0-in.-) diameter single 30-mesh screen |
| | | Fuel: | propane |
| 156 | 1527 (B) | Flame arrester: | 25.4-cm- (10.0-in.-) diameter dual 20-mesh screens |
| | | Fuel: | propane |

APPENDIX B

TABULAR SUMMARY OF STEADY-STATE MEASURED
AIR AND FUEL SYSTEM TEST CONDITIONS

| Test No | Config No | PRO kN/m² | DPO kN/m² | TOT F | PF kN/m² | TFL F | EMF Hz | PV1 kN/m² | TV1 C | TV2 C | TMF C | PM1 kN/m² | TM1 C | T14 C | TB1 C | PA1 kN/m² | DPA1 N/m² | DPA2 N/m² | PAMB kN/m² | VA m/s | MA kg/h | MF kg/h | A/F Ratio | [illegible] ER | HCA ER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 93.68 | [illegible] | [illegible] | [illegible] | 93.044 | 3.0 | [illegible] | 93.041 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .77 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| b | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .84 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| b | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 117.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| L | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 768.4 | [illegible] | [illegible] | 101.7 | [illegible] | [illegible] | 13.8 | [illegible] | 41.8 | 26.1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 786.1 | 14.4 | 124.5 | 101.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 24.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 784 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.1 | 9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| L | [illegible] | [illegible] | [illegible] | [illegible] | 786.5 | [illegible] | [illegible] | 102.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| E | [illegible] | [illegible] | [illegible] | [illegible] | 781.9 | [illegible] | [illegible] | 101.8 | [illegible] | [illegible] | 145.2 | [illegible] | [illegible] | [illegible] | 19.7 | [illegible] | [illegible] | [illegible] | [illegible] | 1.448 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] 7A | [illegible] | [illegible] | [illegible] | 54.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 754.0 | [illegible] | [illegible] | [illegible] | 207.6 | [illegible] | 142.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 761.8 | [illegible] | [illegible] | 102.8 | [illegible] | [illegible] | 136.1 | [illegible] | [illegible] | [illegible] | 13.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

LIQUID FUELS (contd)

| Test No. | Config. No | PBO, $kN/m^2$ | DPO, $kN/m^2$ | TO1, °C | PFL, $kN/m^2$ | TFL °F | FMF, Hz | PV1, $kN/m^2$ | TV1, °C | TV2, °C | TMF, °C | PM1, $kN/m^2$ | TM1, °C | T14, °C | T81, °C | PA1, $kN/m^2$ | DPA1, $N/m^2$ | DPA2, $N/m^2$ | PAMB, $kN/m^2$ | VA, m/s | MA, kg/h | MF, kg/h | A/F Ratio | φ E.R. | HCA E.R. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible]A | [illegible] | 127.87 | [illegible] | [illegible] | 763.5 | 71 | 114.7 | 55.0 | 210.1 | 345.9 | [illegible] | 94.710 | 48.9 | 21.7 | 17.3 | 93.731 | 22.8 | 22.8 | [illegible] | 1.419 | [illegible] | 7.747 | [illegible] | [illegible] | [illegible] |
| B | [illegible] | 128.74 | 0.2331 | [illegible] | [illegible] | 13.6 | 118.6 | [illegible] | 207.3 | 346.8 | [illegible] | 94.53 | 51.8 | [illegible] | 23.1 | [illegible] | [illegible] | 24.8 | [illegible] | [illegible] | [illegible] | 8.016 | [illegible] | [illegible] | [illegible] |
| C | 130 | [illegible] | [illegible] | [illegible] | [illegible] | 14.1 | [illegible] | 102.3 | [illegible] | 348.3 | 168.8 | 94.42 | 49.1 | 28.4 | 21.3 | [illegible] | 24.8 | [illegible] | [illegible] | 1.468 | 105.28 | 8.160 | [illegible] | [illegible] | [illegible] |
| 1512A | 132 | [illegible] | [illegible] | [illegible] | 2199 | [illegible] | [illegible] | 110.4 | 123.8 | 261.1 | 86.6 | 92.986 | 32.8 | [illegible] | 12.8 | 92.676 | 20.7 | [illegible] | [illegible] | [illegible] | [illegible] | 7.376 | [illegible] | [illegible] | [illegible] |
| B | [illegible] | [illegible] | 0.2192 | 56.8 | 2127 | [illegible] | 171.7 | 110.6 | 133.2 | 260.7 | 77.8 | 92.876 | 34.2 | [illegible] | 14.1 | 92.786 | [illegible] | 18.6 | 92.765 | [illegible] | [illegible] | [illegible] | 13.47 | [illegible] | [illegible] |
| C | [illegible] | [illegible] | [illegible] | 56.6 | 2129 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 77.8 | 92.717 | 34.0 | [illegible] | 13.4 | [illegible] | 20.0 | 20.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1513A | [illegible] | 128.67 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 181.1 | 168.7 | 425.1 | 135.7 | 93.910 | 45.2 | [illegible] | [illegible] | 92.800 | [illegible] | 7.65 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| B | [illegible] | [illegible] | 0.2317 | 66.4 | 628.0 | 11.5 | [illegible] | 185.2 | 166.1 | 423.2 | 145.4 | 93.765 | 50.0 | 25.8 | 17.7 | 93.647 | 7.58 | 8.76 | [illegible] | 1.418 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| C | [illegible] | 128.10 | 0.2310 | 66.4 | 606.6 | [illegible] | [illegible] | 187.8 | [illegible] | 421.2 | 143.7 | [illegible] | [illegible] | 28.4 | 17.2 | 93.66 | 6.90 | [illegible] | [illegible] | 1.445 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| D | [illegible] | 127.12 | 0.2337 | 68.6 | 575.5 | [illegible] | 249.2 | 184.9 | 157.2 | 421.1 | 157.3 | N.A. | [illegible] | 27.7 | 21.5 | [illegible] | 3.45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1514A | [illegible] | [illegible] | [illegible] | 65.2 | 502.7 | [illegible] | [illegible] | 173.2 | 161.3 | 423.4 | [illegible] | 94.572 | [illegible] | [illegible] | 16.1 | 94.496 | 11.0 | 11.0 | [illegible] | 1.445 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| B | [illegible] | [illegible] | 0.2224 | 67.9 | 472.7 | 13.4 | 244.4 | [illegible] | [illegible] | 427.4 | 140.5 | 94.179 | 55.4 | 31.1 | [illegible] | 94.131 | 12.4 | 11.7 | 94.117 | 1.457 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| C | 135 | [illegible] | 0.2344 | 70.3 | 499.8 | 14.4 | [illegible] | [illegible] | [illegible] | 427.0 | 145.1 | 94.151 | [illegible] | 32.8 | [illegible] | 94.025 | 12.4 | 12.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1515A | 136 | 128.77 | 0.2379 | 69.8 | 238.5 | [illegible] | [illegible] | 106.9 | [illegible] | 343.7 | 178.7 | 94.496 | 52.6 | 24.5 | 18.6 | 94.372 | 8.76 | [illegible] | 94.386 | [illegible] | [illegible] | 7.777 | [illegible] | [illegible] | [illegible] |
| B | [illegible] | [illegible] | 0.2413 | 69.7 | 218.3 | 14.8 | [illegible] | [illegible] | [illegible] | [illegible] | 180.7 | 94.310 | [illegible] | [illegible] | [illegible] | 94.234 | [illegible] | 10.3 | [illegible] | 1.470 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| C | [illegible] | 127.83 | 0.2420 | 74.0 | 216.1 | [illegible] | [illegible] | [illegible] | [illegible] | 343.7 | 184.0 | 94.131 | 55.5 | [illegible] | 25.7 | 94.041 | 10.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.04 | 0.70 |
| D | [illegible] | 127.41 | 0.2482 | 75.8 | 230.0 | 20.7 | [illegible] | 104.2 | 218.0 | 344.9 | 181.5 | N.A. | [illegible] | 37.4 | [illegible] | [illegible] | 2.76 | 3.45 | [illegible] | 1.527 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1516A | [illegible] | [illegible] | 0.2303 | [illegible] | 540.2 | [illegible] | [illegible] | 105.5 | [illegible] | [illegible] | [illegible] | [illegible] | 42.7 | [illegible] | 15.7 | [illegible] | [illegible] | [illegible] | 93.420 | 1.463 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| B | 138 | [illegible] | 0.2331 | 65.4 | 444.3 | [illegible] | 96.1 | 101.0 | [illegible] | 331.4 | 128.6 | 93.400 | 45.4 | 24.1 | 18.8 | [illegible] | [illegible] | 7.58 | 93.317 | 1.461 | 105.47 | [illegible] | [illegible] | [illegible] | [illegible] |
| C | 138 | 127.14 | [illegible] | [illegible] | 420.5 | 14.6 | 97.2 | [illegible] | 174.2 | 332.7 | 114.7 | 93.055 | 37.1 | [illegible] | 14.4 | 92.919 | [illegible] | 7.58 | 92.972 | 1.464 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| D | 138 | 127.09 | 0.2276 | 61.7 | 408.7 | 15.0 | [illegible] | 104.9 | 188.4 | 334.6 | 113.3 | 93.014 | 37.2 | 22.8 | 14.4 | 92.931 | 7.58 | 7.58 | 92.924 | 1.470 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1517A | 139 | [illegible] | 0.2287 | 58.3 | [illegible] | [illegible] | 173.6 | 112.4 | 157.0 | 320.8 | 136.1 | 93.508 | 42.7 | 15.9 | 10.5 | 93.474 | [illegible] | 12.4 | 93.427 | 1.460 | 106.91 | 10.80 | 9.89 | 1.36 | 0.70 |
| B | 139 | 128.01 | 0.2317 | 61.7 | [illegible] | [illegible] | 172.8 | [illegible] | [illegible] | 240.1 | 128.1 | 93.345 | 46.0 | 19.9 | 15.5 | 93.242 | 7.65 | 8.76 | [illegible] | 1.475 | 105.78 | 10.75 | 9.84 | 1.14 | 0.69 |
| C | 139 | [illegible] | [illegible] | 64.4 | 418.7 | [illegible] | 170.6 | 110.4 | 136.9 | 305.4 | 118.3 | 93.310 | 44.4 | 23.6 | 21.2 | [illegible] | 10.3 | 11.0 | [illegible] | 1.487 | 104.78 | [illegible] | 9.91 | 1.13 | 0.69 |
| D | 140 | 127.34 | [illegible] | [illegible] | [illegible] | [illegible] | 175.5 | 116.4 | 185.8 | 277.8 | 116.7 | [illegible] | 47.0 | 26.4 | [illegible] | 93.220 | 0 | 0 | [illegible] | 1.524 | [illegible] | 10.78 | 9.88 | 1.13 | 0.74 |
| 1518A | 141 | [illegible] | [illegible] | [illegible] | 693.3 | [illegible] | 178.5 | [illegible] | 136.2 | 298.0 | 113.6 | 93.510 | 41.6 | 15.8 | 10.1 | 93.413 | 6.89 | 7.58 | [illegible] | 1.450 | [illegible] | 11.39 | 9.67 | 1.16 | 0.71 |
| B | 141 | [illegible] | [illegible] | [illegible] | [illegible] | 11.4 | 174.0 | 115.8 | 140.1 | [illegible] | 115.5 | [illegible] | 42.1 | 18.8 | 14.8 | [illegible] | [illegible] | [illegible] | 93.448 | 1.450 | [illegible] | [illegible] | 9.65 | 1.16 | 0.71 |
| C | 141 | [illegible] | 0.2441 | [illegible] | 683.7 | [illegible] | 179.1 | 111.5 | 127.1 | 246.6 | 109.0 | [illegible] | 48.7 | 25.1 | 17.3 | 93.462 | 4.83 | 4.83 | 93.455 | 1.516 | 107.64 | [illegible] | 9.84 | 1.14 | 0.72 |
| 1519A | 142 | [illegible] | [illegible] | [illegible] | 2119 | [illegible] | 138.9 | 105.6 | 130.9 | [illegible] | [illegible] | 94.124 | 40.0 | 15.8 | 14.2 | [illegible] | [illegible] | [illegible] | 94.084 | [illegible] | 102.11 | [illegible] | 13.93 | 1.11 | 0.78 |
| B | 142 | [illegible] | [illegible] | [illegible] | 2133 | [illegible] | 145.4 | 106.3 | 137.5 | [illegible] | 106.8 | 94.455 | 44.6 | 23.7 | 19.8 | 94.377 | [illegible] | [illegible] | [illegible] | 1.450 | [illegible] | 7.587 | 13.64 | 1.13 | 0.75 |
| C | 142 | [illegible] | [illegible] | [illegible] | 2150 | [illegible] | 151.3 | 107.8 | 136.8 | 257.4 | 115.3 | 94.282 | [illegible] | 24.5 | [illegible] | 94.220 | 5.52 | [illegible] | [illegible] | [illegible] | 107.17 | 7.816 | 13.70 | 1.13 | 0.75 |
| D | 143 | [illegible] | [illegible] | [illegible] | 2141 | [illegible] | 147.2 | 105.6 | 141.1 | 261.1 | 120.2 | [illegible] | 48.7 | 24.7 | 25.3 | [illegible] | 6.21 | 6.89 | 94.179 | [illegible] | [illegible] | 7.548 | 13.91 | 1.11 | 0.75 |

| Test No. | Config No. | PBL kN | DPL kN | [illegible] | PFL kN | [illegible] | TMF | [illegible] | [illegible] | [illegible] | [illegible] | PMV kN | [illegible] | [illegible] | [illegible] | WAT kN | DFAT | FAT | AMV | [illegible] | [illegible] | [illegible] | AT | [illegible] | [illegible] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | 157.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | [illegible] | | 7.5 | .14 | 0.79 |
| 1520A | [illegible] | | [illegible] | [illegible] | | [illegible] | 152.1 | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | | | [illegible] | | | 3.43 | [illegible] | 0.8[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | 148.1 | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | 3.51 | .14 | [illegible] |
| C | 144 | [illegible] | [illegible] | [illegible] | | [illegible] | 148.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | | 3.51 | .14 | [illegible] |
| 1521A | 145 | [illegible] | [illegible] | [illegible] | [illegible] | | 203.9 | 41.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | 6.83 | 1.16 | .63 |
| [illegible] | 145 | [illegible] | [illegible] | | [illegible] | [illegible] | 201.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | | [illegible] | 6.95 | [illegible] | .64 |
| C | 145 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible]4.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | | | [illegible] | [illegible] | [illegible] | | 6.40 | [illegible] | [illegible] |
| D | 146 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 210.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | | [illegible] | 6.83 | [illegible] | .60 |
| 1522A | 147 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 209.6 | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.71 | [illegible] | [illegible] |
| B | 147 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 206.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | [illegible] | | [illegible] | 6.82 | 1.15 | [illegible] |
| C | 147 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 208.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.83 | 1.15 | 0.66 |
| 1523A | 148 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 155.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.52 | 1.16 | [illegible] |
| B | 148 | [illegible] | [illegible] | [illegible] | [illegible] | 8.[illegible] | 158.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.02 | 1.04 | [illegible] |
| 1524A | 149 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 166.5 | 108.3 | 143.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14.14 | [illegible] | [illegible] |
| 1525A | 151 | 24.[illegible] | [illegible] | [illegible] | [illegible] | 2.4 | 170.9 | [illegible] | 99.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14.01 | 1.12 | .00 |
| 1526A | 153 | 27.00 | [illegible] | [illegible] | [illegible] | [illegible] | 172.4 | 07.9 | 102.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.11 | [illegible] | [illegible] |
| B | 154 | [illegible] | [illegible]496 | [illegible] | [illegible] | [illegible] | 170.5 | [illegible] | 107.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14.18 | 1.10 | [illegible] |
| 1527A | 155 | [illegible] | [illegible]482 | [illegible] | [illegible] | [illegible] | [illegible] | 110.1 | 75.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.73 | [illegible] | [illegible] |
| B | 156 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 182.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.84 | 1.[illegible]3 | [illegible] |

| Test No | Config No | PBO kN/m² | DPO kN/m² | TO1 C | PGF kN/m² | TGF C | DPG kN/m² | PV1 kN/m² | TV1 C | TV2 C | TMF C | PM1 kN/m² | TM1 C | T14 C | TB1 C | PA1 kN/m² | DPA1 N/m² | DPA2 N/m² | PAMB kN/m² | VA m/s | MA kg/h | MFG kg/h | A/FG Ratio | φ ER | HCA ER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1500A | 117 | 129.75 | 0.2296 | 63.8 | 522.9 | 14.7 | 222.1 | 125.5 | 130.1 | 192.3 | 109.9 | 94.79 | 42.6 | 18.8 | 15.6 | 94.133 | 7.6 | 8.3 | 94.637 | 1.137 | 104.69 | 8.119 | 12.59 | 1.15 | 0.79 |
| B | 117 | 128.51 | 0.2344 | [illegible] | 518.5 | 16.9 | 222.0 | 123.3 | 107.7 | 191.4 | 85.6 | 94.79 | 45.9 | 27.7 | 22.7 | 94.441 | 9.0 | 8.3 | 94.454 | 1.457 | 103.06 | 7.923 | 12.91 | 1.15 | [illegible] |
| C | 117 | [illegible] | [illegible] | [illegible] | [illegible] | 9.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.69 | 1.16 | 0.71 |
| 1501A | 118 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 123.6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.06 | 1.14 | [illegible] |
| B | 119 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 24.1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.98 | 1.14 | 0.77 |
| C | 119 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 27.3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.05 | 1.14 | 0.70 |
| D | 119 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 127.2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.61 | 1.17 | 0.70 |
| 1502A | 120 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 124.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.80 | 1.16 | 0.68 |
| B | 121 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 47.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.86 | 1.15 | 0.67 |
| C | 121 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 112.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.82 | 1.15 | 0.67 |
| D | 121 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 224.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 24.9 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.72 | 1.16 | 0.68 |
| 1503A | 122 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 107.3 | [illegible] | 42.8 | [illegible] | 14.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.42 | 1.11 | 0.67 |
| B | 122 | [illegible] | [illegible] | [illegible] | 515.8 | 8.1 | 220.2 | [illegible] | 131.2 | [illegible] | 114.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 12.72 | 1.16 | 0.66 |
| C | 122 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 115.4 | [illegible] | 94.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 77.77 | [illegible] | 12.69 | 1.17 | 0.66 |
| 1505A | 121 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 217.0 | [illegible] | 129.7 | [illegible] | 110.7 | 74.310 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.440 | [illegible] | [illegible] | 13.02 | 1.14 | 0.73 |
| B | 124 | [illegible] | [illegible] | [illegible] | [illegible] | 14.3 | [illegible] | 122.8 | 130.0 | [illegible] | 110.3 | [illegible] | [illegible] | [illegible] | [illegible] | 74.217 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.14 | 1.13 | 0.71 |
| C | 124 | [illegible] | [illegible] | 67.0 | 502.8 | [illegible] | [illegible] | 122.4 | 127.2 | [illegible] | 107.4 | [illegible] | [illegible] | [illegible] | [illegible] | 74.165 | [illegible] | 40.0 | [illegible] | [illegible] | [illegible] | [illegible] | 13.47 | 1.10 | 0.71 |
| D | 124 | [illegible] | [illegible] | [illegible] | 504.7 | 13.7 | [illegible] | [illegible] | 130.9 | [illegible] | 111.7 | 74.144 | [illegible] | 26.9 | [illegible] | [illegible] | [illegible] | 40.0 | [illegible] | 1.436 | [illegible] | [illegible] | 13.06 | 1.12 | 0.72 |
| 1511A | 131 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 213.2 | 121.9 | 126.1 | [illegible] | 104.1 | [illegible] | 42.8 | 15.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.11 | 1.13 | 0.73 |
| B | 131 | [illegible] | [illegible] | [illegible] | 521.8 | [illegible] | 224.9 | 124.8 | 132.2 | [illegible] | 110.8 | [illegible] | [illegible] | [illegible] | 18.7 | [illegible] | [illegible] | [illegible] | 72.765 | [illegible] | 101.77 | [illegible] | 12.61 | 1.18 | 0.74 |
| C | 131 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 223.3 | 124.1 | 133.7 | 206.5 | 112.1 | [illegible] | [illegible] | [illegible] | [illegible] | 72.341 | [illegible] | [illegible] | [illegible] | [illegible] | 101.23 | [illegible] | 12.55 | 1.18 | 0.76 |
| D | 131 | [illegible] | [illegible] | [illegible] | 524.9 | [illegible] | 232.8 | 121.9 | 74.8 | 112.9 | 65.3 | [illegible] | 41.8 | [illegible] | [illegible] | 72.710 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.09 | 1.13 | 0.73 |
| 1524S | 150 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 186.0 | [illegible] | 143.7 | 202.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.50 | 1.10 | 0.95 |
| C | 150 | 126.67 | [illegible] | [illegible] | [illegible] | [illegible] | 198.7 | 119.8 | 144.2 | 199.8 | [illegible] | [illegible] | 47.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.45 | 1.10 | 0.97 |
| 1525B | 152 | [illegible] | [illegible] | [illegible] | 523.4 | 24.0 | 208.0 | 111.0 | 129.1 | 192.6 | 99.5 | [illegible] | 42.7 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.32 | 1.11 | 0.84 |
| C | 152 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 136.7 | 198.7 | 78.8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.41 | 1.10 | 0.83 |

# APPENDIX C

## TABULAR SUMMARY OF TRANSIENT-STATE MEASURED FLAME SPEED AND PEAK PRESSURE RISE

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5.?? | 8.? | N.A.* | NA | NA | NA | NA | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.32 | [illegible] | [illegible] | | [illegible] |
| [illegible]A | [illegible] | [illegible] | [illegible] | 920 | 992 | 4.96 | 1.01 | 7.68 | [illegible] | 1.09 | 7.24 | NA | NA | NA | NA | | | | | | | | | | |
| [illegible] | [illegible] | 9?2 | 718 | 79? | 706 | [illegible] | 7.62 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3.39 | [illegible] | 3.11 | | | | | | | | | | |
| C | [illegible] | 7?? | 834 | 828 | 74? | [illegible] | [illegible] | [illegible] | 7.17 | 7.23 | [illegible] | 2.21 | [illegible] | 2.92 | [illegible] | | | | | | | | | | |
| [illegible] | | 789 | 1085 | [illegible] | 23? | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 3.60 | 2.4? | 1.29 | [illegible] | [illegible] | | | | | | | | | | |
| | [illegible] | 825 | 888 | 839 | [illegible] | [illegible] | 2.90 | [illegible] | [illegible] | 2.38 | 3.67 | 2.68 | [illegible] | [illegible] | [illegible] | | | | | | | | | | |
| | [illegible] | [illegible] | 759 | [illegible] | 840 | [illegible] | [illegible] | [illegible] | [illegible] | 4.92 | 3.98 | 3.24 | 4.36 | 2.77 | [illegible] | | | | | | | | | | |
| [illegible]A | [illegible] | 8?0 | [illegible] | 893 | 802 | [illegible] | [illegible] | 2.56 | 3.11 | 7.38 | 4.23 | 5.?? | [illegible] | [illegible] | [illegible] | | | | | | | | | | |
| B | [illegible] | 729 | 737 | [illegible] | 725 | [illegible] | [illegible] | [illegible] | 4.06 | [illegible] | 5.59 | 2.81 | 2.51 | 2.79 | 2.49 | | | | | | | | | | |
| C | [illegible] | 810 | 718 | 675 | 725 | [illegible] | [illegible] | [illegible] | 1.08 | [illegible] | 4.26 | 3.21 | [illegible] | [illegible] | 1.31 | | | | | | | | | | |
| D | [illegible] | 729 | 756 | 752 | 783 | [illegible] | [illegible] | [illegible] | 3.91 | 2.68 | 3.81 | 2.71 | 2.54 | 1.98 | 2.08 | | | | | | | | | | |
| [illegible]A | [illegible] | 830 | 854 | 846 | 753 | [illegible] | [illegible] | [illegible] | 12.19 | 13.33 | [illegible] | 3.95 | 4.93 | 9.51 | 6.22 | | | | | | | | | | |
| B | [illegible] | 891 | 912 | 876 | 783 | 4.62 | [illegible] | [illegible] | 13.55 | 15.64 | [illegible] | 3.95 | [illegible] | 9.51 | 4.98 | | | | | | | | | | |
| C | [illegible] | 891 | 892 | 883 | 859 | [illegible] | 3.26 | [illegible] | 13.59 | 18.02 | 2.02 | 4.33 | [illegible] | 9.51 | 6.22 | | | | | | | | | | |
| 1500[illegible] | [illegible] | NO | IGN | ITIO | N | | | | | | | | | | | | | | | | | | | | |
| A | 117 | 1060 | 1099 | 1028 | 980 | 5.25 | 8.16 | 7.43 | 9.38 | 5.64 | 12.19 | 4.78 | 7.62 | 5.94 | 6.22 | | | | | | | | | | |
| [illegible] | 117 | 035 | 1122 | 960 | 980 | 5.28 | 1.87 | 8.71 | 17.62 | 6.78 | 15.45 | [illegible] | [illegible] | [illegible] | 8.30 | | | | | | | | | | |
| [illegible]A | 118 | 1013 | 965 | 914 | 763 | 5.56 | 7.34 | 7.7? | 7.18 | 6.45 | 13.77 | 3.95 | 4.36 | 4.95 | 4.98 | | | | | | | | | | |
| B | 119 | 966 | 987 | 1005 | 938 | 3.54 | 3.40 | 2.67 | 3.56 | 3.06 | 6.21 | 3.78 | 2.77 | 2.29 | 2.26 | | | | | | | | | | |
| C | 119 | 848 | 898 | 845 | 785 | 3.66 | 3.77 | 3.29 | 2.74 | 2.83 | 7.32 | [illegible] | [illegible] | 2.10 | 2.08 | | | | | | | | | | |
| D | 119 | 895 | 920 | 914 | 872 | 2.23 | 2.89 | 2.31 | 2.46 | 2.69 | 9.39 | 4.51 | 3.37 | 2.49 | 1.18 | | | | | | | | | | |
| 1502A | 120 | 1251 | 1571 | 1671 | 1482 | [illegible] | 10.84 | 9.95 | 7.78 | 7.50 | 11.24 | [illegible] | [illegible] | 2.43 | 6.22 | 236.5 | 178.5 | 264.4 | >440 | >440 | 490 | [illegible] | [illegible] | 27.3? | >1800 |
| B | 121 | 769 | 763 | 747 | 698 | 3.63 | 2.74 | 3.11 | 2.47 | 1.51 | 5.44 | 4.55 | 3.81 | 4.35 | 3.56 | | | | | | | | | | |
| C | 121 | 794 | 740 | 632 | 678 | 2.31 | 4.08 | 3.06 | 2.57 | 0.94 | 4.08 | [illegible] | 5.08 | 1.35 | 1.81 | | | | | | | | | | |
| D | 121 | 818 | 708 | 858 | 872 | 4.67 | 3.76 | 2.85 | [illegible] | 2.00 | 5.19 | 5.19 | 3.81 | 3.31 | 2.08 | | | | | | | | | | |
| 1503A | 122 | 1342 | 1412 | 1234 | 1158 | 5.38 | [illegible] | 7.20 | 7.11 | 20.61 | 12.20 | 5.19 | 5.08 | 7.42 | 8.30 | 147 | 246.? | 285.8 | [illegible] | [illegible] | 3.68 | 8.30 | 4.33 | [illegible] | >9?? |
| B | 122 | 1301 | 1099 | 1120 | 1010 | 6.79 | 9.31 | 11.28 | 9.49 | 11.28 | 15.13 | 6.79 | 7.62 | 7.41 | 8.30 | 150.6 | 252.0 | 278.2 | [illegible] | >[illegible] | [illegible] | [illegible] | 5.92 | [illegible] | >900 |
| C | 122 | 1036 | 1053 | 1005 | 1158 | 4.86 | 7.66 | 7.7? | 7.03 | 10.97 | 8.92 | 4.90 | 6.10 | 7.43 | 8.30 | 146.9 | 147.3 | 256.? | [illegible] | [illegible] | 4.28 | 5.3? | 3.69 | [illegible] | [illegible] |
| 1504A | 123 | 1319 | 1418 | 1325 | 1273 | 3.89 | 4.71 | 6.55 | 6.77 | 6.15 | 7.53 | 3.40 | 2.81 | 4.25 | 4.98 | | | | | | | | | | |
| B | 123 | 1439 | 1442 | 1417 | 1414 | 4.30 | 5.79 | 9.56 | 10.95 | 11.37 | 12.55 | 3.82 | 4.32 | 5.94 | 8.30 | | | | | | | | | | |
| C | 123 | 1413 | 1396 | 1393 | 1265 | 4.91 | 6.15 | 8.82 | 10.49 | 16.01 | 16.90 | 4.38 | 5.08 | 8.68 | 6.22 | | | | | | | | | | |
| 1505A | 124 | 1389 | 1526 | 1531 | 1396 | 8.52 | 8.89 | 8.76 | 13.93 | 16.54 | 32.29 | 3.32 | 2.51 | 4.85 | 4.98 | | | | | | | | | | |

*N.A. - Not available.

| | | Flame Chamber Test Data | | | | | | | | | | | | | | Inlet Piping Test Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Peak Pressure Rise | | | | Flame Sensor Flame Speeds | | | | | | Photographic Flame Speeds | | | | Peak Pressure Rise | | | | | Flame Sensor Flame Speeds | | | | |
| Test No | Config No | DP81 $N/m^2$ | DP83 $N/m^2$ | DP85 $N/m^2$ | DP87 $N/m^2$ | F81 F82 m/s | F82 F83 m/s | F83 F84 m/s | F84 F85 m/s | F85 F86 m/s | F88 F87 m/s | SA S1 m/s | S1 S2 m/s | S2 S3 m/s | S3 S4 m/s | P73 $kN/m^2$ | P72 $kN/m^2$ | P71 $kN/m^2$ | P21 $kN/m^2$ | P12 $kN/m^2$ | F81 F73 m/s | F73 F72 m/s | F72 F71 m/s | F71 F21 m/s | F21 F12 m/s |
| [illegible] | [illegible] | 1131 | 1055 | 1097 | 1243 | 7.38 | 6.95 | 7.20 | 7.81 | 7.75 | 19.36 | 3.41 | 2.34 | 5.94 | 4.98 | | | | | | | | | | |
| C | [illegible] | 1319 | 369 | [illegible] | 1221 | 6.24 | 6.88 | 7.88 | 11.74 | 12.74 | 15.36 | 7.83 | 7.39 | 4.95 | 7.98 | | | | | | | | | | |
| D | [illegible] | 1579 | 1524 | 1599 | 1504 | 6.45 | 9.01 | 13.47 | 15.54 | 30.30 | 23.74 | 6.13 | 6.10 | 7.43 | 12.44 | | | | | | | | | | |
| [illegible] | [illegible] | 727 | 718 | 731 | 824 | 2.67 | 3.61 | 1.21 | 2.36 | 1.63 | 2.07 | N.A.[a] | N.A | N.A | N.A. | | | | | | | | | | |
| [illegible] | [illegible] | 755 | 945 | 955 | 975 | 2.83 | 3.19 | 1.74 | 2.30 | 1.38 | 3.56 | | | | | | | | | | | | | | |
| C | [illegible] | 742 | 1032 | 1097 | 1113 | 3.57 | 7.19 | 3.97 | 2.73 | 1.77 | 3.72 | | | | | | | | | | | | | | |
| [illegible] | [illegible] | 707 | 809 | [illegible] | 1069 | 6.38 | 6.31 | 2.69 | 3.92 | 2.32 | 2.27 | | | | | | | | | | | | | | |
| [illegible] A | 126 | NO | IG | NIT | ION | | | | | | | | | | | | | | | | | | | | |
| B | 126 | 1198 | 1336 | 1073 | 972 | 6.47 | 4.46 | 2.32 | NA | NA | N.A | | | | | | | | | | | | | | |
| [illegible] | [illegible] | 781 | 907 | 981 | 971 | 4.02 | 4.82 | 7.23 | 5.16 | 4.97 | 8.51 | | | | | 153.2 | 187.6 | 155.3 | 107.1 | 97.8 | 2.00 | 4.12 | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | 958 | 994 | 1005 | 930 | 3.9 | 6.58 | 2.97 | 1.60 | 0.84 | 0.64 | | | | | | | | | | | | | | |
| [illegible] | [illegible] | 1045 | 1036 | 1045 | 1069 | 3.69 | 6.70 | 7.82 | 5.43 | 3.11 | 3.67 | | | | | | | | | | | | | | |
| [illegible] | 28 | 914 | 994 | 965 | 1148 | 3.83 | 7.56 | 6.13 | 3.76 | 1.25 | 2.04 | | | | | | | | | | | | | | |
| | [illegible] | 1176 | 1318 | 1125 | 1148 | 4.10 | 8.67 | 5.06 | 4.78 | [illegible] | 3.57 | | | | | | | | | | | | | | |
| | [illegible] | 1359 | 1274 | 1429 | 1287 | 4.61 | [illegible] | 9.64 | 7.61 | 3.72 | 4.35 | N.A | NA | NA | N.A. | | | | | | | | | | |
| [illegible] | [illegible] | 1595 | 1569 | 1647 | 1527 | 2.64 | 3.36 | 16.34 | 25.86 | 42.79 | 54.01 | 2.72 | NA | 3.72 | [illegible] | 314.4 | [illegible] | [illegible] | [illegible] | [illegible] | 3.63 | [illegible] | [illegible] | 4.80 | 2.00 |
| [illegible] | 30 | 1071 | 1060 | 1045 | 916 | 2.95 | 3.21 | 8.15 | 30.45 | 72.11 | 88.15 | 2.35 | [illegible] | 3.30 | 4.38 | 346.6 | [illegible] | [illegible] | >440 | >440 | 3.43 | [illegible] | [illegible] | 4.82 | 2.02 |
| [illegible] | [illegible] | 1595 | 1526 | 1307 | 1317 | 4.57 | 5.49 | 25.15 | 27.14 | [illegible] | 60.35 | NA | NA | 4.95 | 4.94 | 367.6 | 57.5 | 265.3 | [illegible] | >440 | [illegible] | [illegible] | [illegible] | 3.96 | 2.06 |
| [illegible] | [illegible] | 811 | 858 | 864 | 894 | 2.86 | 1.41 | [illegible] | 2.55 | 2.60 | [illegible] | 1.65 | 2.02 | NA | NA | | | | | | | | | | |
| [illegible] | [illegible] | 1089 | 1101 | 1205 | 1282 | 5.36 | 9.13 | 8.25 | 2.54 | 2.00 | 2.65 | 2.17 | 3.39 | 4.25 | 2.76 | | | | | | | | | | |
| [illegible] | [illegible] | 1132 | 1034 | 1226 | 1263 | 5.74 | 6.43 | 7.49 | 2.74 | 2.47 | 2.69 | 2.12 | 4.35 | 3.30 | NA | | | | | | | | | | |
| [illegible] | [illegible] | 666 | 715 | 733 | 719 | 5.24 | 5.34 | 6.99 | 9.83 | [illegible] | 17.47 | 3.98 | 3.39 | 5.94 | 2.76 | | | | | | | | | | |
| [illegible] | 131 | 666 | 781 | 708 | 874 | 1.59 | 5.91 | 5.63 | [illegible] | 12.80 | 14.63 | 4.71 | 4.36 | 5.94 | 4.98 | | | | | | | | | | |
| [illegible] | 131 | 745 | 930 | 460 | 777 | 8.60 | 8.03 | 8.86 | 10.38 | 11.37 | 12.39 | 5.75 | 6.10 | 5.94 | 8.30 | | | | | | | | | | |
| [illegible] | 131 | 1312 | 1165 | 1234 | 1166 | 9.23 | 8.82 | 7.84 | 13.64 | 11.65 | [illegible] | 5.75 | 6.10 | 7.43 | 12.44 | 365.1 | 208.5 | [illegible] | [illegible] | [illegible] | [illegible] | 6.98 | 8.44 | [illegible] | >180 |
| [illegible]A | 132 | .740 | 558 | 868 | 574 | 4.35 | 4.11 | [illegible] | 2.86 | [illegible] | NA | 3.04 | 5.81 | 3.72 | [illegible] | | | | | | | | | | |
| 3 | 132 | 1307 | 1454 | 1280 | 1127 | 4.61 | 5.62 | 5.57 | 7.36 | 9.66 | 9.51 | 3.23 | 4.36 | 4.95 | 4.98 | | | | | | | | | | |
| [illegible] | 132 | 1061 | 954 | 1090 | 1088 | 5.35 | 5.75 | 5.09 | 7.22 | 11.71 | 9.27 | 3.04 | 4.36 | 3.94 | 4.15 | | | | | | | | | | |
| [illegible]A | 133 | 980 | 934 | 941 | 733 | 5.36 | 6.22 | 4.68 | 2.94 | NA | N.A | 3.19 | 4.36 | 4.93 | 6.22 | | | | | | | | | | |
| [illegible] | 133 | 784 | 771 | 762 | 933 | 3.50 | 7.55 | 3.93 | 2.34 | NA | NA | 2.52 | 3.81 | 3.72 | 8.56 | | | | | | | | | | |
| | 133 | 691 | 721 | 784 | 777 | 3.16 | 7.69 | 2.83 | 1.34 | NA | NA | 2.67 | 3.81 | 4.25 | [illegible] | | | | | | | | | | |
| | 134 | 734 | 841 | 852 | [illegible] | 1.46 | 6.63 | 5.07 | 4.09 | NA | N.A | [illegible] | 4.36 | 5.94 | 4.98 | 186.1 | [illegible] | 6.0 | 322.2 | 306.1 | 2.19 | 2.98 | 3.80 | [illegible] | [illegible] |

[a]N.A. - Not available.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | 67 | [illegible] | 92 | [illegible] | [illegible] | [illegible] | [illegible] | 4.5[illegible] | NA | NA | [illegible] | [illegible] | 4.79 | [illegible] |
| B | 13[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5.2[illegible] | [illegible]40 | 3.45 | NA | NA | 3.[illegible]3 | 6[illegible] | [illegible] | 3.[illegible] |
| C | 135 | [illegible] | [illegible] | [illegible]53 | [illegible] | 5.[illegible] | 5.99 | 6.06 | [illegible].50 | NA | NA | 3.[illegible]3 | 6[illegible] | [illegible] | [illegible] |
| 1515A | 136 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible].68 | 6.35 | 1.72 | 5.66 | 2.37 | 2.39 | 2[illegible] | [illegible] | [illegible] |
| B | 136 | 875 | [illegible] | 872 | [illegible] | 5.64 | 6.15 | 6.63 | 2.92 | [illegible] | 2.[illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| C | 136 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]0 | [illegible]30 | 4.94 | 4.[illegible]3 | [illegible] | [illegible] | 6[illegible] | [illegible] | [illegible]9[illegible] |
| D | 137 | [illegible] | [illegible] | [illegible]2 | [illegible] | 7.[illegible] | 8.[illegible] | 7.[illegible] | [illegible].03 | 4.00 | [illegible]3[illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 1516A | 138 | [illegible] | [illegible] | 652 | [illegible] | 3.[illegible] | [illegible] | [illegible] | 1.5[illegible] | [illegible] | [illegible]7 | [illegible] | [illegible] | [illegible] | [illegible] |
| B | 138 | [illegible] | [illegible] | 493 | 525 | [illegible] | [illegible] | [illegible] | 2.82 | [illegible] | 2.12 | 3.[illegible] | [illegible] | 3.[illegible]2 | [illegible] |
| C | 138 | [illegible] | [illegible] | 695 | 622 | [illegible] | 2.23 | [illegible] | 2.[illegible] | [illegible] | 2.22 | 3.[illegible] | [illegible] | 4.25 | [illegible] |
| D | 138 | [illegible] | [illegible] | [illegible]63 | 64[illegible] | [illegible] | [illegible] | [illegible] | 3.[illegible] | 3.[illegible] | [illegible] | 2.[illegible]9 | [illegible] | 3.[illegible]2 | 2.[illegible] |
| 1517A | 139 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.[illegible] | [illegible] | 9.[illegible] | NA | 2.43 | 2.[illegible] | [illegible] | [illegible] |
| B | 139 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 9.[illegible] | 3.04 | 9.[illegible] | [illegible] | 3.79 | [illegible] | [illegible] | [illegible]8 |
| C | 139 | [illegible] | 474 | [illegible] | 1069 | 6.39 | [illegible] | 8.[illegible] | [illegible] | [illegible] | NA | 4.33 | [illegible] | [illegible] | [illegible] |
| D | 140 | 610 | 633 | 695 | 622 | 7.60 | [illegible] | [illegible] | 15.74 | 6.9 | N.A. | 5.64 | 6.[illegible] | [illegible]43 | 8.[illegible] |
| 1518A | 141 | [illegible]57 | 1407 | [illegible]8 | [illegible]24 | 7.89 | [illegible] | 4.42 | 7.[illegible] | NA | NA | 3.68 | [illegible] | [illegible]94 | 6.72 |
| B | 141 | 840 | 811 | [illegible] | 874 | 4.6 | 5.71 | 7.34 | NA | NA | NA | 2.94 | [illegible] | 4.95 | [illegible]5 |
| C | 141 | 840 | 1169 | [illegible] | [illegible] | 3.36 | 6.25 | [illegible] | NA | NA | NA | 3.6[illegible] | 3.08 | [illegible] | 4.98 |
| 1519A | 142 | 962 | 925 | 960 | 9[illegible]8 | 2.25 | [illegible]76 | 3.[illegible] | 2.75 | 1.63 | 2.53 | 1.96 | 2.03 | 2.39 | NA |
| B | 142 | 876 | 90[illegible] | 10[illegible]8 | 1028 | 4.25 | 5.57 | 2.[illegible]2 | 2.99 | 1.61 | 2.31 | 2.39 | 2.34 | 2.48 | 3.56 |
| C | 142 | 876 | 925 | 9[illegible] | 968 | 3.10 | [illegible] | [illegible]68 | [illegible]61 | 4.[illegible] | 3.2 | [illegible] | [illegible] | [illegible] | [illegible] |
| D | 142 | 940 | 1047 | 960 | 1024 | 2.98 | 5.39 | 6.22 | 5.80 | 4.49 | 4.60 | [illegible] | [illegible] | [illegible] | [illegible] |
| E | 143 | 748 | 755 | 84[illegible] | 968 | 4.17 | [illegible].6[illegible] | 7.84 | 3.63 | 2.86 | 4.58 | [illegible] | [illegible] | [illegible] | [illegible] |
| 1520A | 144 | 945 | 921 | 937 | 84[illegible] | 2.92 | 3.15 | 2.65 | 2.[illegible] | 0.44 | [illegible] | [illegible] | 2.[illegible] | 3.[illegible] | [illegible] |
| B | 144 | 840 | 877 | 868 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.39 | 4.30 | [illegible] | [illegible] |
| C | 144 | [illegible] | [illegible] | [illegible] | 1028 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2.6[illegible] | 3.39 | [illegible] | [illegible] |
| 1521A | 145 | 1067 | [illegible] | [illegible] | 968 | [illegible] | [illegible] | [illegible] | [illegible] | 6.[illegible] | [illegible] | 3.[illegible] | [illegible] | 79[illegible] | 6.22 |
| B | 145 | [illegible] | [illegible] | [illegible] | [illegible]65 | [illegible] | [illegible].36 | [illegible] | [illegible] | [illegible] | [illegible] | 3.[illegible] | [illegible] | [illegible] | 7.[illegible] |
| C | 145 | 1133 | 1329 | 1280 | [illegible] | 5.3[illegible] | 7.36 | [illegible] | [illegible] | 17.81 | 21.66 | 5.6[illegible] | [illegible] | [illegible] | [illegible] |
| D | 146 | 1005 | [illegible] | 1280 | 1371 | 4.93 | [illegible]33 | [illegible]37 | 8.35 | 10.[illegible] | 15.[illegible] | [illegible].33 | 6.[illegible] | [illegible] | 6.22 |
| 1522A | 147 | [illegible] | 1261 | 1031 | [illegible]9 | 5.[illegible] | 6.21 | 6.98 | 8.31 | 5.69 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| B | 147 | 1176 | 1389 | [illegible] | 1422 | 6.[illegible] | [illegible] | 8.35 | [illegible] | 13.8[illegible] | 16.[illegible] | [illegible] | 6.10 | [illegible]94 | 8.[illegible] |
| C | 147 | [illegible] | [illegible] | [illegible] | [illegible]29 | 5.[illegible] | 7.45 | 7.74 | [illegible]33 | 8.05 | 6.16 | [illegible] | [illegible] | [illegible] | 8.30 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| D | 137 | 2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| D | 140 | 2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| E | 143 | 207 | 158 | 113 | 24[illegible] | [illegible] | 2.6 | [illegible] | [illegible] | [illegible] | [illegible] |
| D | 146 | [illegible]9 | [illegible] | 23[illegible] | [illegible]0 | NA | 32[illegible] | [illegible] | 1[illegible] | [illegible] | [illegible] |

N.A. = Not [illegible]

# APPENDIX D

## TABULAR SUMMARY OF AVERAGED MEASURED FLAME SPEED AND PEAK PRESSURE RISE FOR FUELS

| | Flame Chamber Test Data | | | | | | | | | | | | | | [illegible] Data | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Peak Pressure Rise | | | | Flame Sensor Flame Speed | | | | | | Photographic Flame Speed | | | | Peak Pressure Rise | | | | | Flame Sensor Flame Speed | | | | |
| Fuel Type | DP81 $N/m^2$ | DP83 $N/m^2$ | DP85 $N/m^2$ | DP87 $N/m^2$ | F81 F82 m/s | F82 F83 m/s | F83 F84 m/s | F84 F85 m/s | F85 F86 m/s | F86 F87 m/s | S0 S1 m/s | S1 S2 m/s | S2 S3 m/s | S3 S4 m/s | P73 $kN/m^2$ | P72 $kN/m^2$ | P71 $kN/m^2$ | P21 $kN/m^2$ | P12 $kN/m^2$ | F81 F73 m/s | F73 F72 m/s | F72 F71 m/s | F71 F21 m/s | F21 F12 m/s |
| [illegible] (a) | 39 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 7.21 | [illegible] | 10.65 | 13.63 | 3.40 | [illegible] | 6.19 | [illegible] | [illegible] | 265 | [illegible] | [illegible] | [illegible] | 2.32 | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] (b) | [illegible] | 530 | 862 | 818 | 2.97 | 2.66 | [illegible] | 3.13 | 7.12 | 4.16 | 3.38 | [illegible] | 7.02 | [illegible] | — | | | | | | | | | |
| [illegible] (a) | 1101 | [illegible] | [illegible] | [illegible] | 6.60 | 7.63 | 8.64 | 10.41 | 13.27 | 16.27 | 4.75 | 4.76 | 5.87 | [illegible] | [illegible] | 215 | 277 | >410 | >410 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] (b) | [illegible] | 955 | [illegible] | 904 | 4.35 | 4.98 | [illegible] | 4.12 | 3.33 | 7.83 | [illegible] | [illegible] | [illegible] | [illegible] | 337 | [illegible] | [illegible] | >410 | >410 | [illegible] | [illegible] | [illegible] | [illegible] | >8.0 |
| [illegible] | [illegible] | 997 | 1033 | 1068 | 4.22 | 6.01 | 5.04 | 3.34 | 2.38 | 2.92 | 2.42 | 3.21 | 3.90 | 3.92 | 183 | 140 | [illegible] | [illegible] | [illegible] | 2.00 | 4.12 | [illegible] | 4.69 | [illegible] |
| METHANOL | [illegible] | 629 | [illegible] | [illegible] | 4.35 | 5.52 | 4.66 | 3.28 | N.A. | N.A. | [illegible] | 4.62 | [illegible] | [illegible] | [illegible] | 135 | [illegible] | 322 | 300 | 2.19 | 2.48 | 3.80 | [illegible] | [illegible] |
| TOLUENE | 640 | 645 | 661 | 724 | 5.42 | 6.27 | 6.14 | 3.08 | 4.28 | 2.65 | [illegible] | [illegible] | [illegible] | [illegible] | 207 | 155 | 121 | NA | N.A. | [illegible] | [illegible] | [illegible] | [illegible] | NA |
| DIETHYL ETHER | 892 | [illegible] | 964 | [illegible] | 5.61 | 6.06 | 6.67 | 11.95 | [illegible] | N.A. | [illegible] | 4.10 | [illegible] | 5.57 | 257 | 166 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| BUTANE | 894 | 913 | 930 | 965 | 3.62 | 5.07 | 3.72 | 3.10 | 2.29 | 2.71 | 2.90 | 3.58 | [illegible] | [illegible] | 209 | [illegible] | [illegible] | [illegible] | N.A. | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| ACETALDEHYDE | 1050 | 1135 | 1096 | 1128 | 5.30 | 6.98 | 7.23 | 9.50 | 9.81 | 12.11 | 4.64 | 5.38 | 5.94 | 6.93 | 319 | 187 | 237 | [illegible] | N.A. | 3.22 | [illegible] | [illegible] | [illegible] | [illegible] |

[a]Igniter position upstream.

[b]Igniter position downstream.

APPENDIX E

TABULAR SUMMARY OF TEMPERATURE MEASUREMENTS
FOR SUSTAINED BURNING TESTS

| Test No | Config No | Time s | TBA °C | TBB °C | TBC °C | TBD °C | TBE °C | TBF °C |
|---|---|---|---|---|---|---|---|---|
| 1524A | 149 | 0 | [illegible] | 14.2 | 19.9 | 18.8 | 18.1 | 22.2 |
| | | 120 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 240 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 360 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 480 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 600 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 720 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 840 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 960 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1080 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1200 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1320 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1440 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1560 | 60.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1680 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1800 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1860 | [illegible] | [illegible] | [illegible] | [illegible] | 175.3 | [illegible] |
| | | 1920 | 152.1 | [illegible] | [illegible] | 915.7 | 210.1 | 27.3 |
| | | | | | | | | |
| 1524B | 150 | 0 | 28.3 | 26.9 | 27.1 | 27.1 | 26.1 | 30.0 |
| | | 60 | [illegible] | [illegible] | [illegible] | [illegible] | 26.3 | [illegible] |
| | | 90 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 120 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 150 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 180 | [illegible] | [illegible] | [illegible] | 878.4 | 27.9 | [illegible] |
| | | 210 | [illegible] | [illegible] | [illegible] | 912.7 | 37.4 | [illegible] |
| | | 240 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 270 | [illegible] | 812.2 | [illegible] | 917.0 | 714.3 | [illegible] |
| | | 300 | [illegible] | 743.0 | [illegible] | 919.7 | [illegible] | [illegible] |
| | | 330 | [illegible] | [illegible] | [illegible] | 891.2 | [illegible] | 30.3 |
| | | 360 | [illegible] | [illegible] | 31.4 | 878.6 | 874.7 | 31.9 |
| | | 390 | [illegible] | [illegible] | [illegible] | 915.9 | [illegible] | 49.4 |

| Test No | Config No | Time s | TBA °C | TBB °C | TBC °C | TBD °C | TBE °C | TBF °C | TBG °C |
|---|---|---|---|---|---|---|---|---|---|
| 1524B | 150 | 420 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 450 | 810.2 | 896.9 | [illegible] | [illegible] | 913.6 | [illegible] | |
| | | | | | | | | | |
| 1524C | 150 | 0 | 36.8 | 28.0 | 27.1 | 33.8 | 27.9 | 32.7 | |
| | | 60 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 90 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 120 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 150 | [illegible] | [illegible] | [illegible] | 881.1 | [illegible] | [illegible] | |
| | | 180 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 210 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 240 | [illegible] | [illegible] | [illegible] | 881.4 | [illegible] | [illegible] | |
| | | 270 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 300 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 330 | 781.5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |
| | | 360 | [illegible] | [illegible] | [illegible] | [illegible] | 718.3 | 281.1 | |
| | | 390 | [illegible] | 712.0 | [illegible] | 825.0 | [illegible] | 528.3 | |
| | | 420 | 771.3 | [illegible] | [illegible] | 824.8 | [illegible] | 575.7 | |
| | | 450 | 763.4 | 969.9 | 446.2 | [illegible] | 972.6 | 305.1 | |
| | | | | | | | | | |
| 1525A | 151 | 0 | 27.5 | 26.0 | 25.8 | 25.5 | 24.2 | 27.9 | 26.4 |
| | | 120 | 36.4 | [illegible] | [illegible] | [illegible] | [illegible] | 28.5 | [illegible] |
| | | 240 | 43.0 | 27.1 | [illegible] | 77.4 | [illegible] | 28.8 | [illegible] |
| | | 360 | 48.6 | [illegible] | [illegible] | [illegible] | 24.8 | [illegible] | [illegible] |
| | | 480 | 54.4 | [illegible] | 26.1 | [illegible] | 24.4 | 28.1 | [illegible] |
| | | 600 | [illegible] | [illegible] | [illegible] | 78.1 | 24.8 | [illegible] | [illegible] |
| | | 720 | [illegible] | [illegible] | [illegible] | 77.1 | [illegible] | [illegible] | [illegible] |
| | | 840 | 77.4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 960 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 27.7 | [illegible] |
| | | 1080 | [illegible] | 27.4 | 27.1 | [illegible] | [illegible] | 27.1 | [illegible] |
| | | 1200 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | 1320 | 105.1 | [illegible] | [illegible] | 76.7 | [illegible] | 30.1 | [illegible] |
| | | 1440 | 110.3 | 27.5 | [illegible] | 76.0 | 25.4 | 27.6 | [illegible] |

| Test No. | Config. No. | Time, s | TBA, °C | TBB, °C | TBC, °C | TBD, °C | TBE, °C | TBF, °C | TBG, °C |
|---|---|---|---|---|---|---|---|---|---|
| 1525A | 151 | 1560 | 116.6 | 27.5 | 27.1 | 75.6 | [illegible] | 24.2 | 333.3 |
| | | 1690 | [illegible] | 28.0 | 27.5 | 75.8 | 26.3 | [illegible] | 333.4 |
| | | 1800 | [illegible] | 28.1 | 27.9 | 75.6 | 26.9 | 30.1 | 333.9 |
| | | 1860 | 127.5 | 28.9 | 28.2 | 35.6 | 27.2 | 30.4 | 75.1 |
| | | | | | | | | | |
| 1525B | 152 | 0 | 27.9 | 28.3 | 28.6 | 28.9 | 27.4 | 31.3 | 30.3 |
| | | 5 | 28.7 | 28.3 | 28.6 | 32.1 | [illegible] | 31.3 | [illegible] |
| | | 10 | 31.1 | 28.2 | 28.5 | 41.9 | 27.6 | 31.3 | 181.8 |
| | | 15 | 33.4 | 28.2 | 28.4 | 52.0 | 27.6 | 31.3 | 278.6 |
| | | 20 | 35.2 | 28.3 | 28.4 | 60.8 | 27.6 | 31.3 | 349.2 |
| | | 25 | 36.6 | 28.3 | 28.5 | 68.6 | 27.5 | 31.3 | 404.5 |
| | | 30 | [illegible] | 28.3 | 28.4 | 75.5 | 27.6 | 31.2 | 461.8 |
| | | 35 | 37.1 | 28.3 | 28.5 | 81.5 | 27.6 | 31.1 | 497.3 |
| | | 40 | 40.1 | 28.4 | 28.6 | 87.7 | 27.6 | 31.3 | 538.1 |
| | | 41 | [illegible] | [illegible] | 28.4 | 88.8 | 27.6 | 31.3 | 546.1 |
| | | 42 | 40.8 | [illegible] | 28.3 | 70.3 | 27.5 | 31.2 | 554.7 |
| | | 43 | 41.1 | 28.2 | 28.3 | 71.8 | 27.5 | 31.2 | 541.8 |
| | | 44 | 65.3 | 65.4 | 89.8 | 109.6 | [illegible] | 117.3 | 529.2 |
| | | 45 | 66.7 | 67.6 | 74.7 | 107.6 | [illegible] | 115.4 | 514.7 |
| | | 50 | 59.6 | 69.9 | 111.3 | 104.8 | 67.3 | 108.4 | 442.2 |
| | | | | | | | | | |
| 1525C | 152 | 0 | FLAME-THROUGH AT IGNITION | | | | | | |
| | | | | | | | | | |
| 1526A | 153 | 0 | 24.3 | — | — | — | — | — | — |
| | | 120 | 80.8 | — | — | — | — | | — |
| | | 240 | 82.0 | | — | — | — | | — |
| | | 360 | 84.4 | — | — | — | | — | — |
| | | 480 | 86.0 | | — | — | — | | — |
| | | 600 | [illegible] | — | | | | | |
| | | 720 | [illegible] | — | — | | — | | |
| | | 840 | [illegible] | | | | — | — | |
| | | 960 | [illegible] | — | | | | | — |

| Test No. | Config. No. | Time, s | TBA, °C | TBB, °C |
|---|---|---|---|---|
| 1526A | 153 | 1080 | 74.0 | — |
| | | 1200 | [illegible] | — |
| | | 1320 | 77.3 | — |
| | | 1440 | 77.8 | — |
| | | 1560 | 78.4 | |
| | | 1680 | 100.0 | |
| | | 1800 | 102.2 | |
| | | 1860 | 65.6 | |
| | | | | |
| 1526B | 154 | 0 | 32.4 | 30.9 |
| | | 120 | 45.9 | 71.8 |
| | | 240 | 47.6 | 92.2 |
| | | 360 | 48.8 | [illegible] |
| | | 480 | 47.8 | 95.4 |
| | | 600 | 48.3 | 75.9 |
| | | 720 | 49.8 | 77.0 |
| | | 840 | 50.3 | [illegible] |
| | | 960 | 51.1 | 100.5 |
| | | 1080 | 51.6 | 101.4 |
| | | 1200 | 51.3 | [illegible] |
| | | 1320 | 52.4 | 103.0 |
| | | 1440 | 53.7 | 108.8 |
| | | 1560 | 54.4 | 107.9 |
| | | 1680 | 54.4 | 107.3 |
| | | 1800 | 54.8 | 110.5 |
| | | 1860 | 325 | 65.6 |
| | | | | |
| 1527A | 155 | 0 | 26.5 | |
| | | 120 | [illegible] | |
| | | 240 | [illegible] | |
| | | 360 | [illegible] | |
| | | 480 | [illegible] | — |

| Test No. | Config. No. | Time, s | TBA, °C | TBB, °C |
|---|---|---|---|---|
| 1527A | 155 | 600 | 290.2 | — |
| | | 720 | [illegible] | — |
| | | 840 | [illegible] | |
| | | 960 | [illegible] | — |
| | | 1080 | [illegible] | |
| | | 1200 | [illegible] | |
| | | 1320 | [illegible] | |
| | | 1440 | [illegible] | |
| | | 1560 | 274.8 | |
| | | 1680 | [illegible] | |
| | | 1800 | [illegible] | |
| | | 1860 | 110.3 | |
| | | | | |
| 1527B | 156 | 0 | 36.6 | 38.4 |
| | | 120 | [illegible] | [illegible] |
| | | 240 | [illegible] | [illegible] |
| | | 360 | [illegible] | 187.3 |
| | | 480 | [illegible] | [illegible] |
| | | 600 | [illegible] | [illegible] |
| | | 720 | [illegible] | [illegible] |
| | | 840 | [illegible] | 202.8 |
| | | 960 | [illegible] | 194.9 |
| | | 1080 | [illegible] | [illegible] |
| | | 1200 | 65.5 | 188.7 |
| | | 1320 | [illegible] | 179.0 |
| | | 1440 | [illegible] | [illegible] |
| | | 1560 | [illegible] | [illegible] |
| | | 1680 | [illegible] | [illegible] |
| | | 1800 | [illegible] | [illegible] |
| | | 1830 | 67.7 | [illegible] |
| | | 1860 | 47.7 | 103.5 |

DATE

ILME